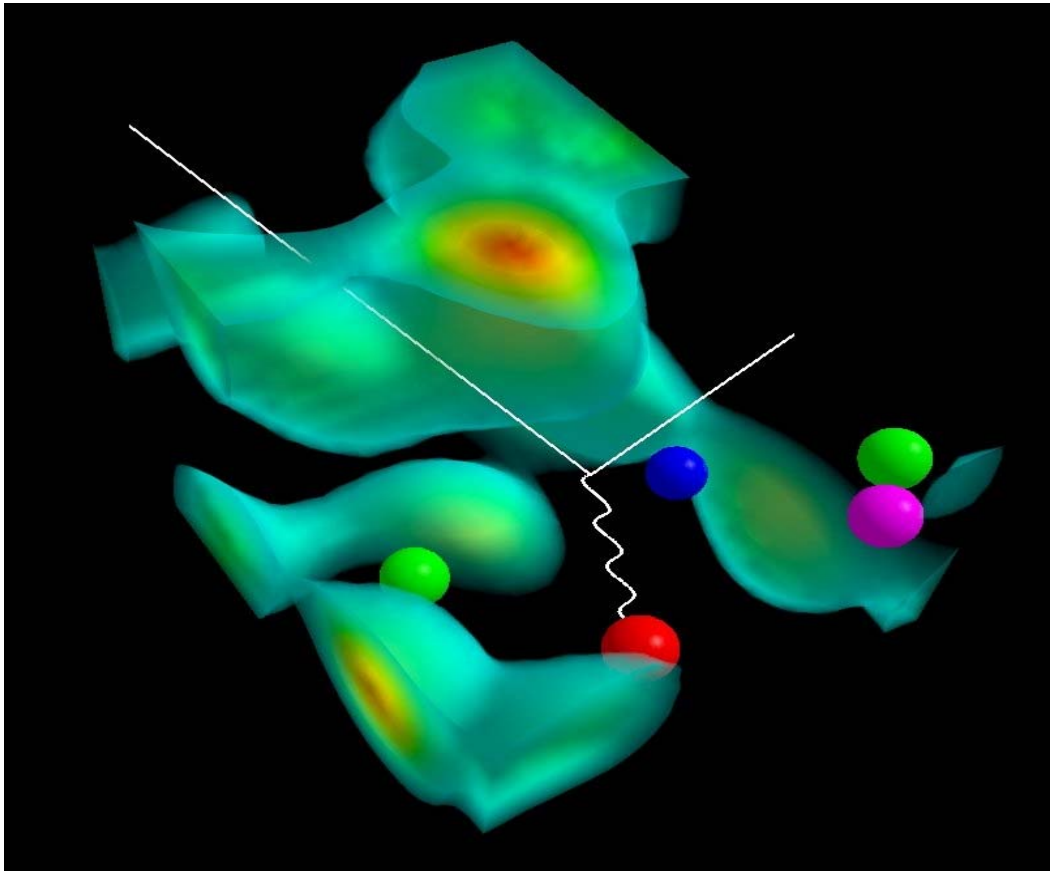
The Resolution of the Proton Spin Crisis



Anthony W. Thomas

JLab: October 5th 2007

Outline

- A reminder: the proton spin crisis
- Progress over the last 20 years
- The resolution of the problem
  - one-gluon-exchange
  - the pion cloud
  - input from lattice QCD
- GPDs at the JLab 12 GeV Upgrade – angular momentum

The EMC "Spin Crisis"

$$\int_0^1 dx\, g_1^p(x) = \underline{(\Delta u - \Delta d)}/12 + \underline{(\Delta u + \Delta d - 2\Delta s)}/36$$

$$+ \underline{(\Delta u + \Delta d + \Delta s)}/9$$

(up to QCD radiative corrections)

g^3_A : from β decay of n

naively fraction of proton 'spin' carried by its quarks

g^8_A : hyperon β decay

$$\Sigma_{inv} \equiv \Sigma\,(Q^2 = \infty)$$

Ancient History of the Spin Crisis

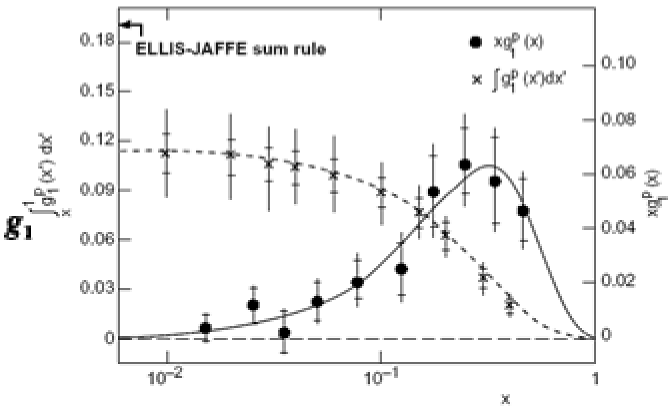
- **EMC Spin Paper: 22 Dec 87 - 19 May 88**
- Brodsky et al. Skyrme: 22 Feb 88 - 19 May 88
- Schreiber-Thomas CBM: 17 May 88 - 8 Dec 88
- Myhrer-Thomas OGE: 13 June 88 - 1 Sept 88

(neither paper could explain reduction to only 14%!)

- Efremov-Teryaev Anomaly: 25 May 88
- Altarelli-Ross Anomaly: 29 June 88 - 29 Sept 88

Volume 206, number 2 PHYSICS LETTERS B 19 May 1988

A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION g_1 IN DEEP INELASTIC MUON–PROTON SCATTERING



European Muon Collaboration

Aachen, CERN, Freiburg, Heidelberg, Lancaster, LAPP (Annecy), Liverpool, Marseille, Mons, Oxford, Rutherford, Sheffield, Turin, Uppsala, Warsaw, Wuppertal, Yale

J. ASHMAN [a], B. BADELEK [b,1], G. BAUM [c,2], J. BEAUFAYS [d], C.P. BEE [e], C BENCHOUK [f],

(93 authors)

The spin asymmetry in deep inelastic scattering of longitudinally polarised muons by longitudinally polarised protons has been measured over a large x range ($0.01 < x < 0.7$). The spin-dependent structure function $g_1(x)$ for the proton has been determined and its integral over x found to be $0.114 \pm 0.012 \pm 0.026$, in disagreement with the Ellis–Jaffe sum rule. Assuming the validity of the Bjorken sum rule, this result implies a significant negative value for the integral of g_1 for the neutron. These values for the integrals of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon.

$\Sigma = 14 \pm 3 \pm 10$ % :

i.e. 86% of spin of p NOT carried by its quarks

Ancient History of the Spin Crisis

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Volume 206, number 2 PHYSICS LETTERS B 19 May 1988

CHIRAL SYMMETRY AND THE SPIN OF THE PROTON ☆

Stanley J. BRODSKY [a], John ELLIS [a,b1] and Marek KARLINER [a]

[a] *Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA*

[b] *CERN, CH-1211 Geneva 23, Switzerland*

Received 22 February 1988

Recent EMC data on the spin-dependent proton structure function suggest that very little of the proton spin is due to the helicity of its constituent quarks. We argue that, at leading order in the $1/N_c$ expansion, none of the proton spin would be carried by quarks in the chiral limit where $m_q=0$. This result is derived in the Skyrme model, which is also used to estimate quark contribution to the proton spin when chiral symmetry and SU(3) are broken: this contribution turns out to be small. Therefore, even in the real world most of the proton spin is due to gluons and/or orbital angular momentum, as suggested by the EMC. We mention other experiments to test this suggestion.

Cohen: NO **Data: NO**

Ancient History of the Spin Crisis

- EMC Spin Paper: 22 Dec 87 - 19 May 88
- Brodsky et al. Skyrme: 22 Feb 88 - 19 May 88
- Schreiber-Thomas CBM: 17 May 88 - 8 Dec 88
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ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
ДУБНА

E2-88-287

A.V.Efremov, O.V.Teryaev*

SPIN STRUCTURE OF THE NUCLEON AND TRIANGLE ANOMALY

Submitted to "Nuclear Physics"

25 May 1988

Volume 212, number 3 PHYSICS LETTERS B 29 September 1988

THE ANOMALOUS GLUON CONTRIBUTION TO POLARIZED LEPTOPRODUCTION

G. ALTARELLI and G.G. ROSS [1]
CERN, CH-1211 Geneva 23, Switzerland

Received 29 June 1988

We show that, due to the anomaly, the gluon contribution to the first moment of the polarized proton structure function, as measured in deep inelastic scattering, is not suppressed by a power of the strong coupling evaluated at a large scale. As a result, the EMC result for the first moment of polarized proton electroproduction is consistent with a large quark spin component.

$$\Sigma_{\text{naïve}} \rightarrow \Sigma_{\text{naïve}} - N_f \frac{\alpha_s (Q^2)}{2\pi} \Delta G (Q^2)$$

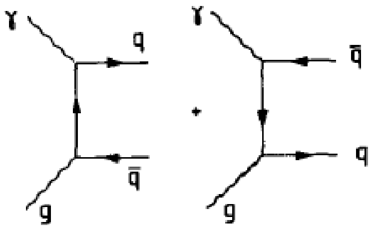


Fig. 1. Diagrams contributing to a finite mixing of order α_s between g_1^p and the polarized gluon parton density.

and QCD evolution $\Rightarrow \alpha_s(Q^2)\, \Delta\, G(Q^2)$ does not vanish

and polarized gluons would resolve crisis

HOW MUCH?

Scale of the Gluon Contribution

At 3 GeV^2 $\alpha_s \sim 0.3$

and $N_f = 3$, so IF all of the

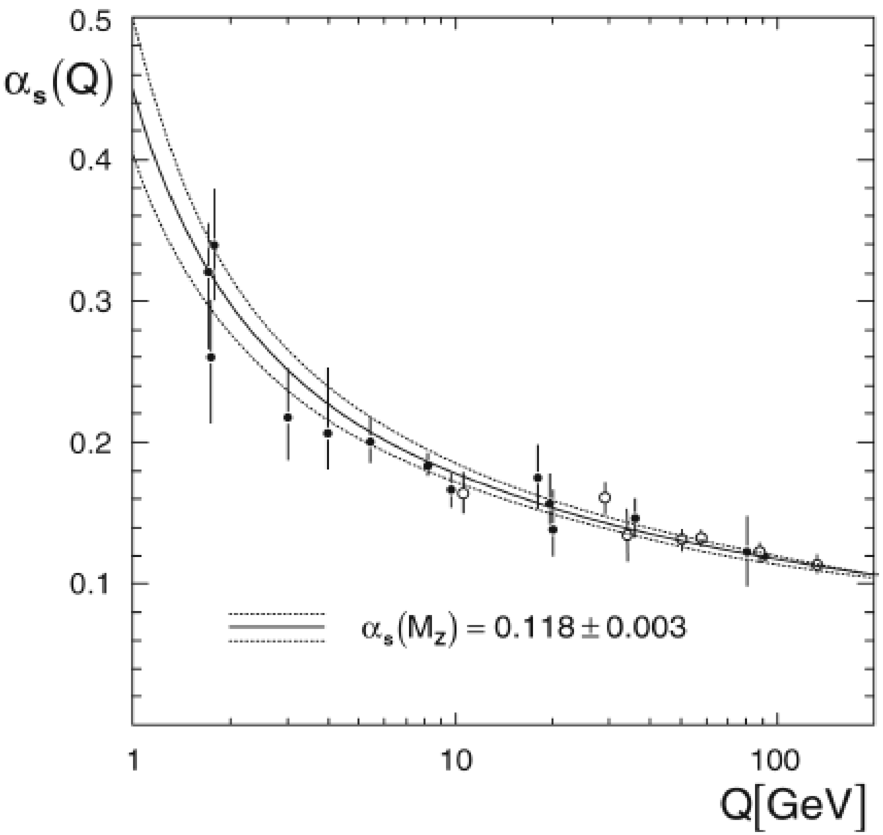
N spin carried by quarks is

cancelled by gluons:

$$\Delta G = + \frac{2 * \pi * 1}{3 * 0.3} \sim +6$$

…actually $\Delta G \sim + 4$ better

- a truly remarkable result



for which no physical explanation was ever offered

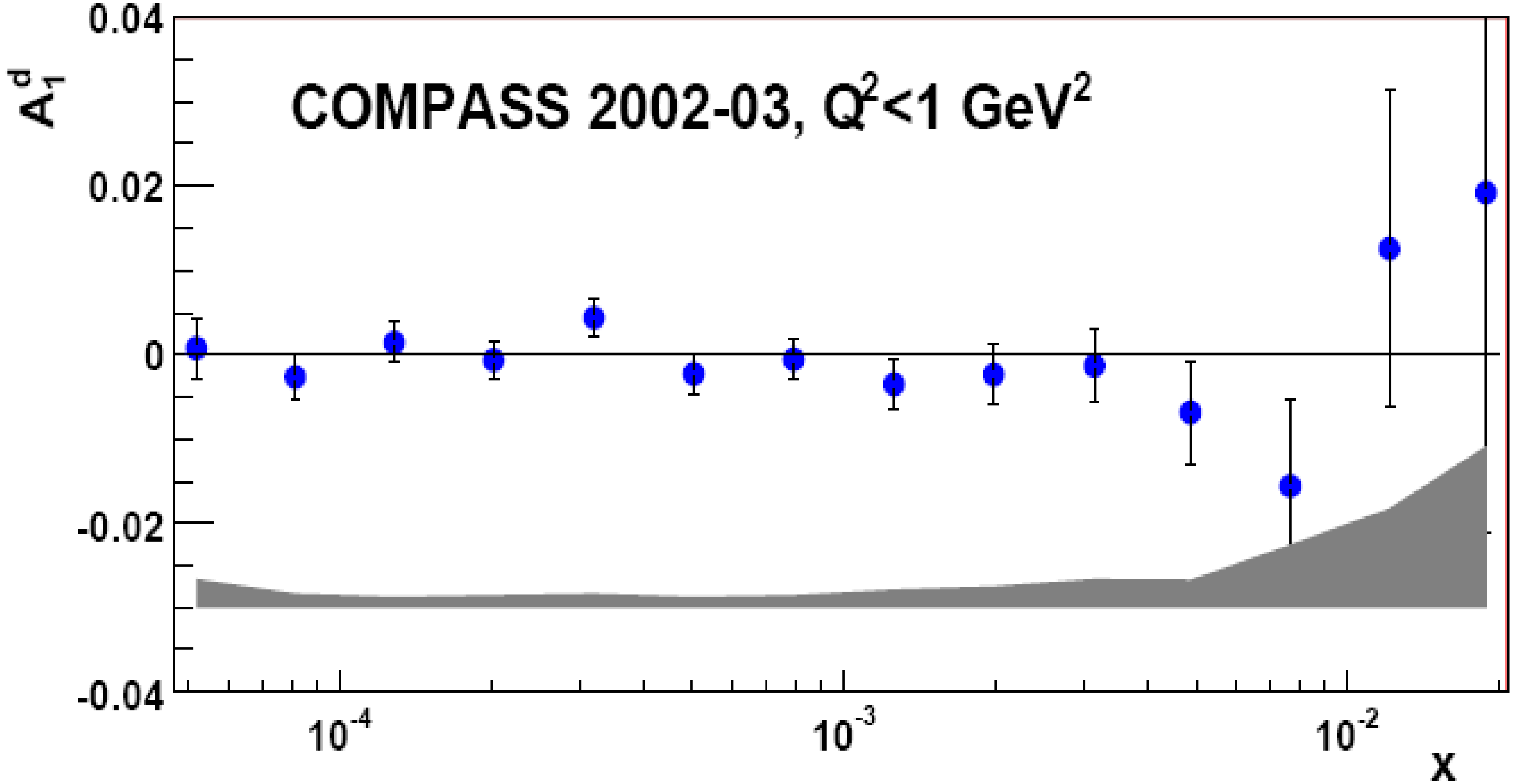
This spurred a tremendous experimental effort

- DIS measurements of spin structure functions of polarized p, d, ^{3}He (and ^{6}Li) at SLAC, CERN, Hermes, JLab

- Direct search for high-p_T hadrons at Hermes, COMPASS, RHIC to directly search for effects of polarized glue in the p

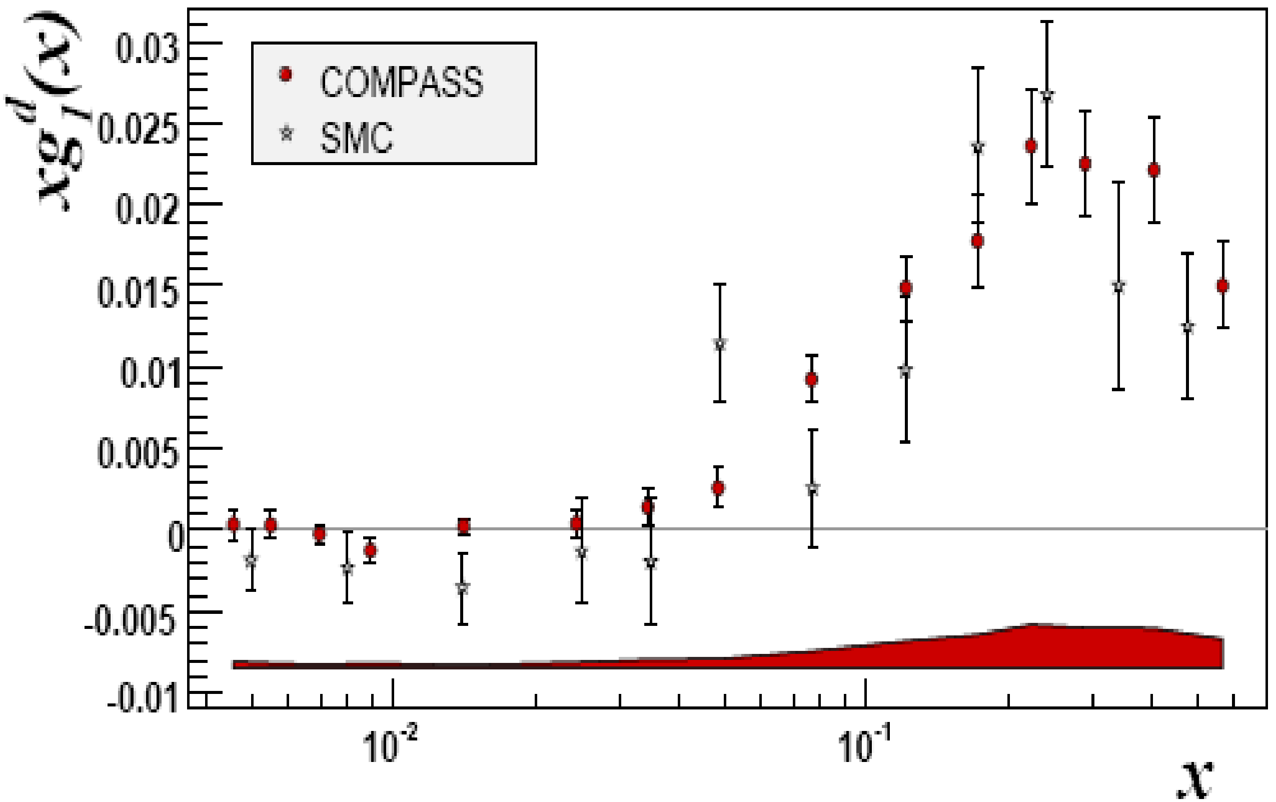
- This effort has lasted the past 20 years, with great success

Asymmetry for $Q^2 < 1\ (\mathrm{GeV/c})^2$



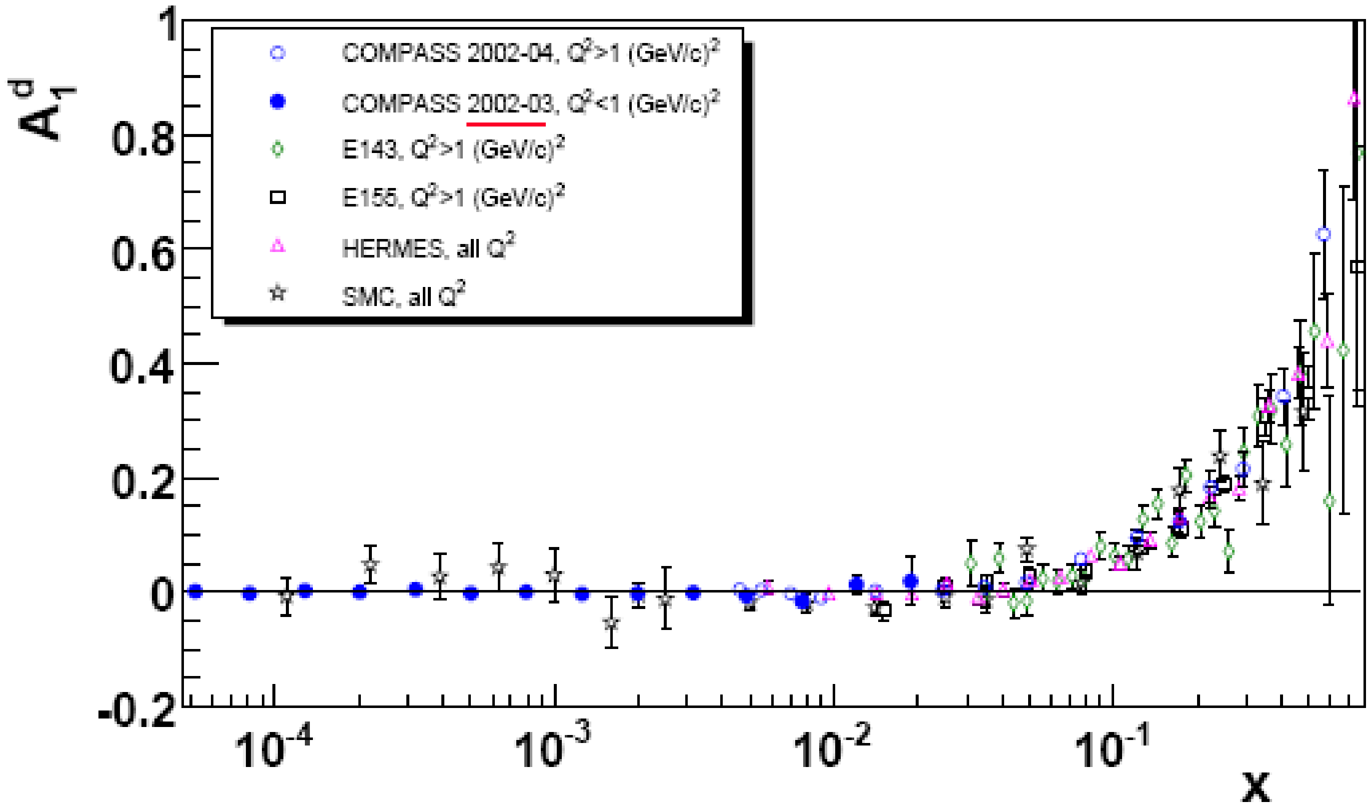
Kabuβ – Pacific Spin 07

$g_1(x)$ at measured Q^2



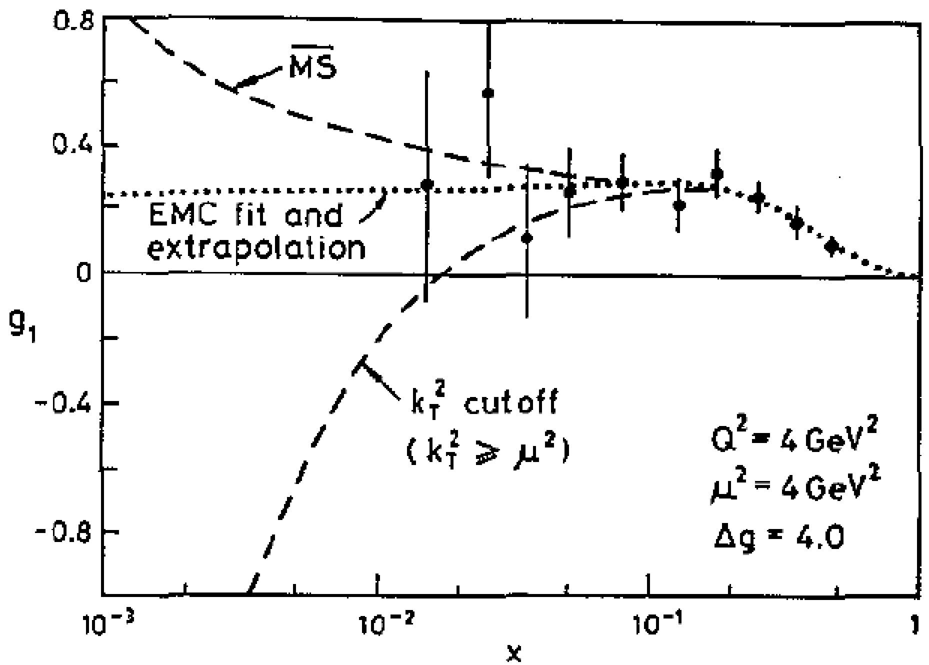
$$g_1 = A_1 \cdot \frac{F_2}{2x(1+R)}$$

Comparison with other experiments



- very good agreement with SMC (the only other experiment at low x)
- factor 10–20 improvement of statistical errors compared to SMC

Effect of Photon-Gluon Fusion – with axial anomaly

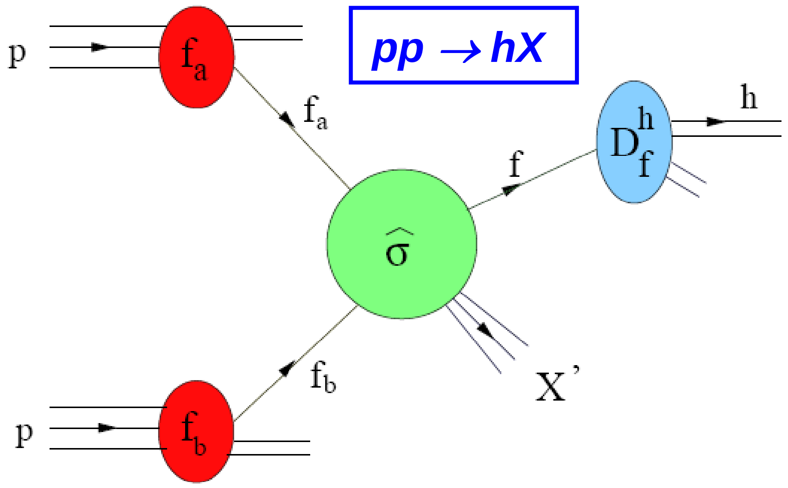


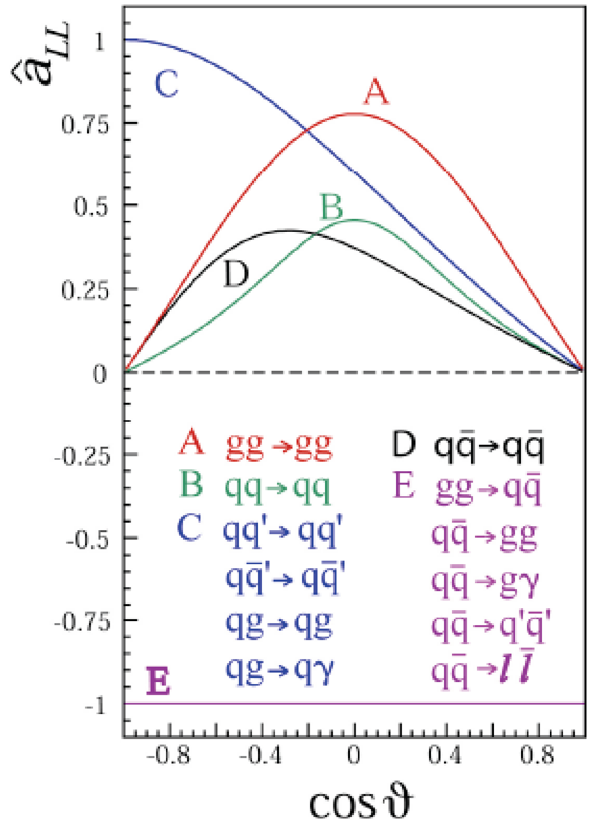
Bass and Thomas,
J. Phys. G19 (1993) 925

COMPASS: at x $\sim 3 \times 10^{-3}$: $|x\, g_1^d| < 0.001$
and hence $|g_1^d| < 0.3$, c.f. >1.0 with $\Delta G = 4$
and data at lower x makes it much worse

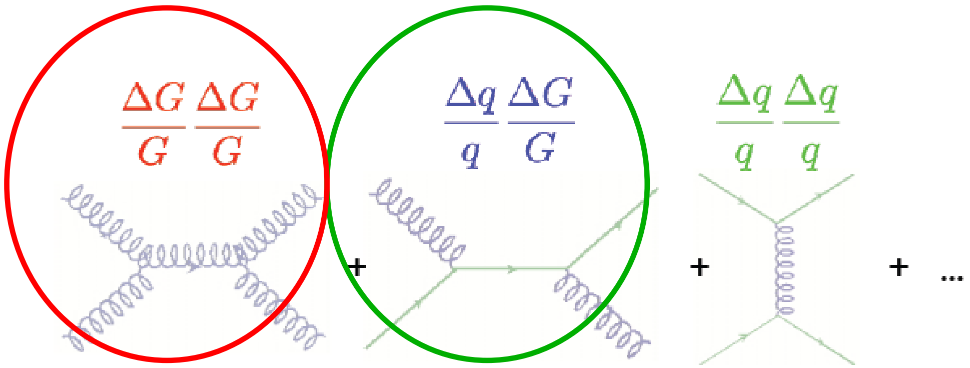
RHIC

Probing ΔG in pol. pp collisions





$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \cdot \hat{a}_{LL}^{f_a f_b \to fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \otimes D_f^h}$$

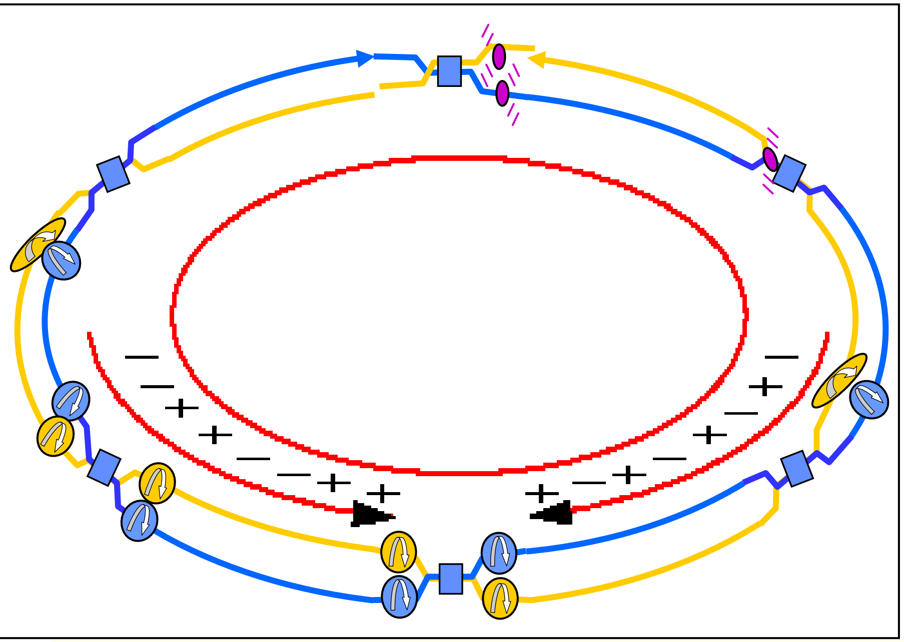


Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

Next 7 slides from Bazilevsky (PHENIX) Pacific SPIN07

Measuring A_{LL}

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \qquad R = \frac{L_{++}}{L_{+-}}$$



(N) Yield

(R) Relative Luminosity

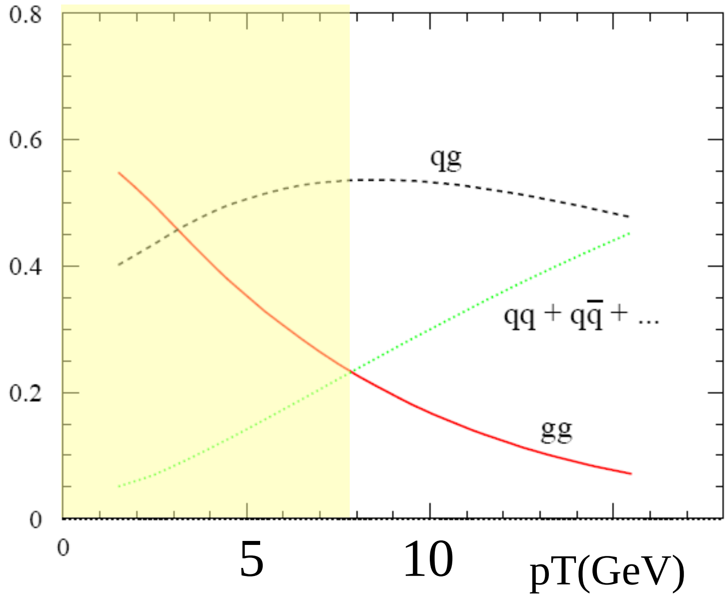
- ✓ BBC vs ZDC

(P) Polarization

- ✓ RHIC Polarimeter (at 12 o'clock)
- ✓ Local Polarimeters (SMD&ZDC)

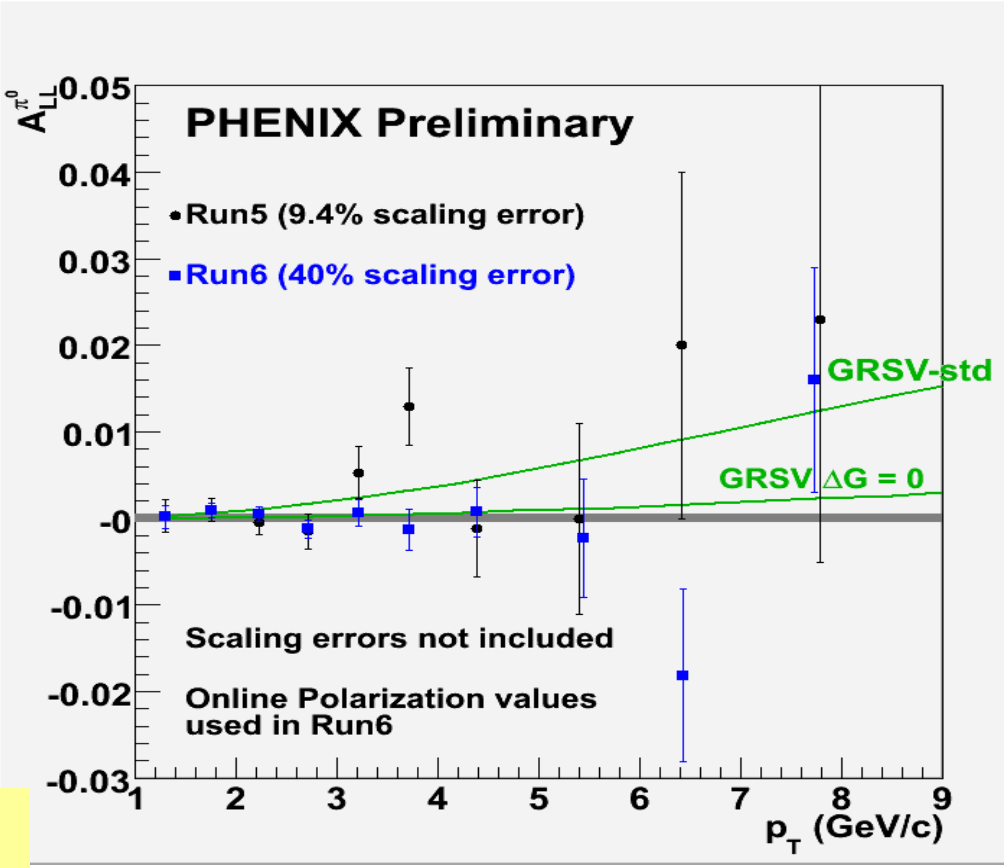
- ✓ Bunch spin configuration alternates every 106 ns
- ✓ Data for all bunch spin configurations are collected at the same time

⇒ Possibility for false asymmetries are greatly reduced



A_{LL}: π^0

PHENIX Preliminary Run6 ($\sqrt{s}$=200 GeV)



GRSV model:

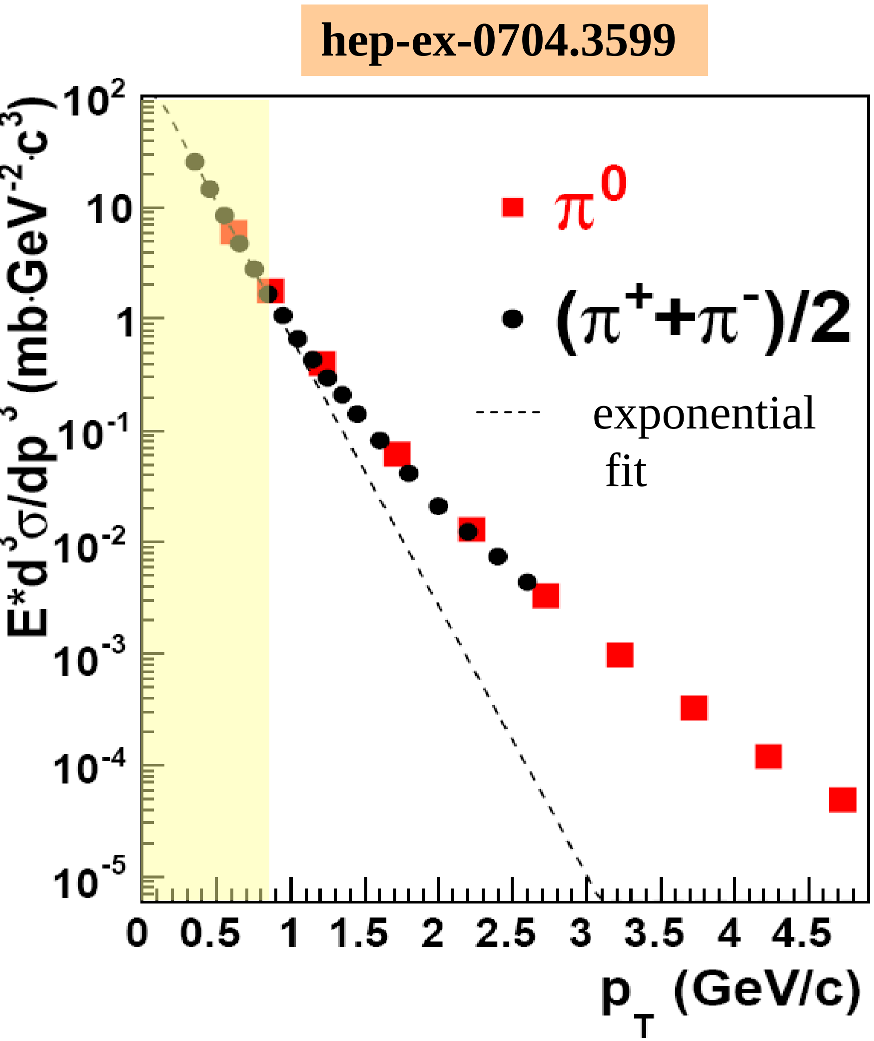
"$\Delta G = 0$": $\Delta G(Q^2=1GeV^2)=0.1$

"ΔG = std": $\Delta G(Q^2=1GeV^2)=0.4$

Stat. uncertainties are on level to distinguish "std" and "0" scenarios? …

Run3,4,5: PRL 93, 202002; PRD 73, 091102; hep-ex-0704.3599

From soft to hard



Exponent ($e^{-\alpha \cdot pT}$) describes our pion cross section data perfectly well at p_T<~1 GeV/c (dominated by soft physics):

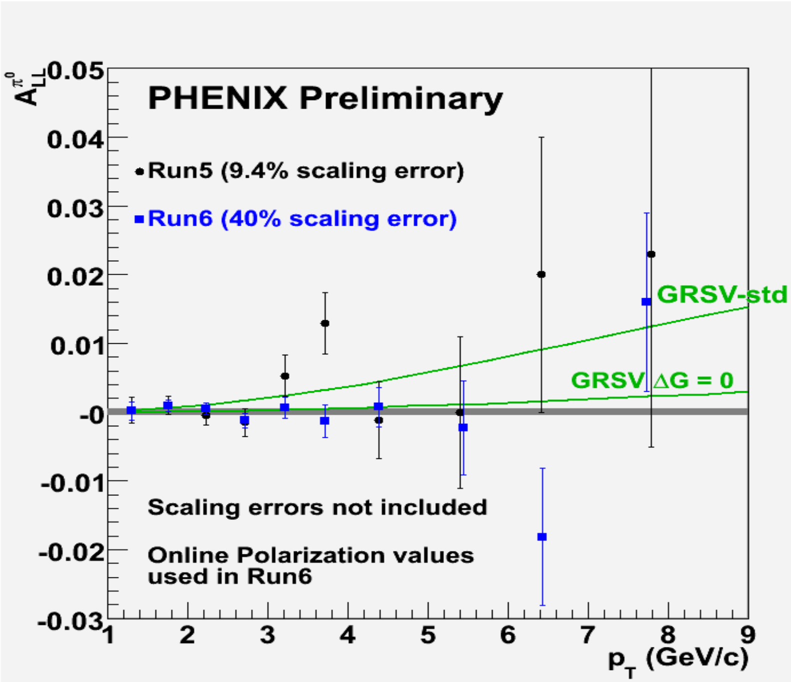
α=5.56±0.02 (GeV/c)$^{-1}$

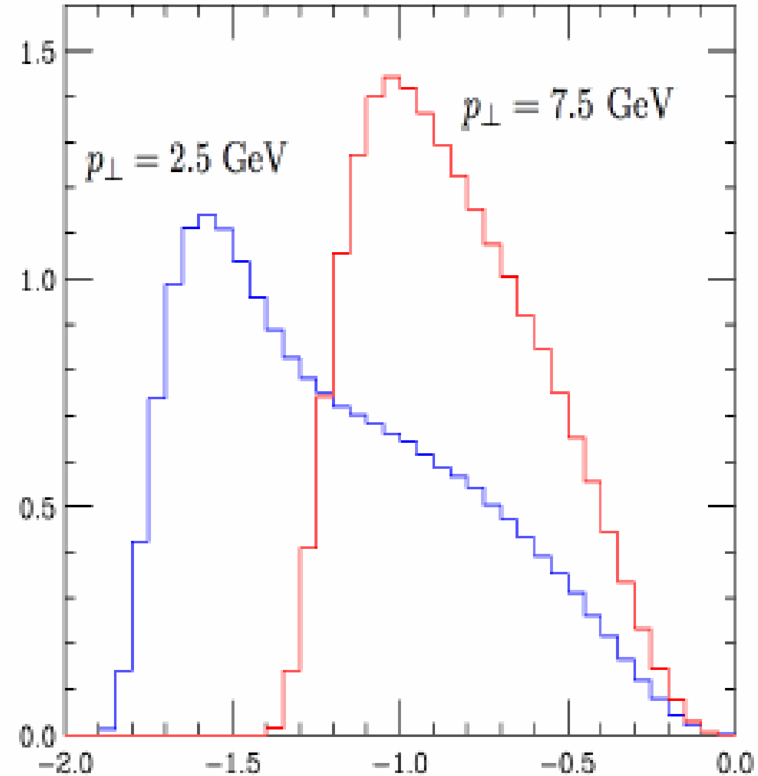
χ^2/NDF=6.2/3

Assume that exponent describes soft physics contribution also at higher pTs ⇒ soft physics contribution at pT>2 GeV/c is <10%

For ΔG constrain use pi0 A_{LL} data at pT>2 GeV/c

From p_T to x_{gluon}





$\mathrm{Log}_{10}(x_{gluon})$

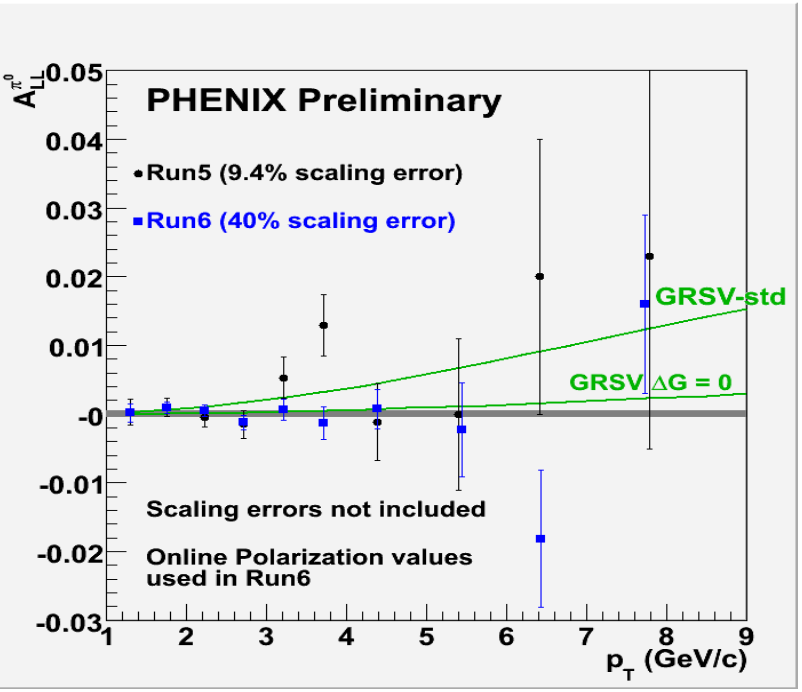
NLO pQCD: π^0 p_T=2–9 GeV/c → x_{gluon}=0.02–0.3

- ✓ GRSV model: $\Delta G(x_{gluon}=0.02\rightarrow0.3) \sim 0.6\cdot\Delta G(x_{gluon}=0\rightarrow1)$

Each p_T bin corresponds to a wide range in x_{gluon}, heavily overlapping with other p_T bins

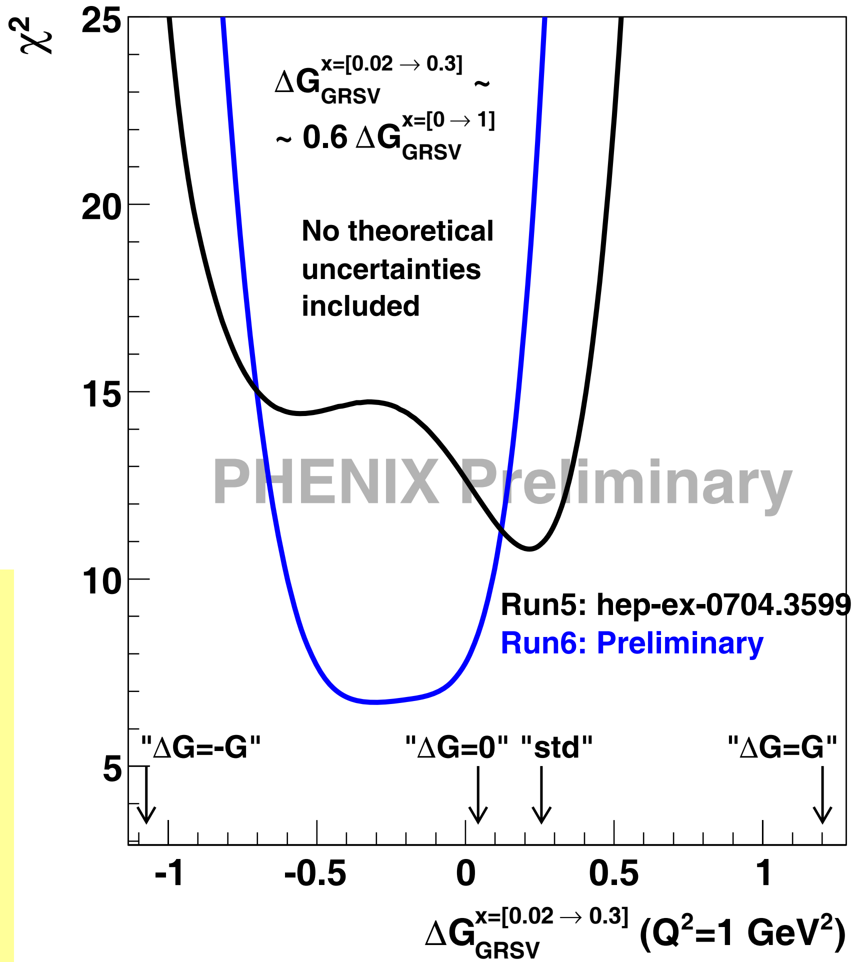
- ✓ These data is not much sensitive to variation of $\Delta G(x_{gluon})$ within our x range
- ✓ Any quantitative analysis should assume some $\Delta G(x_{gluon})$ shape

From A_{LL} to ΔG (with GRSV)



$\Rightarrow$

Calc. by W.Vogelsang and M.Stratmann



"std" scenario, $\Delta G(Q^2\!=\!1\text{GeV}^2)=0.4$, is excluded by data on >3 sigma level: $\chi^2(\text{std})-\chi^2_{\text{min}}>9$

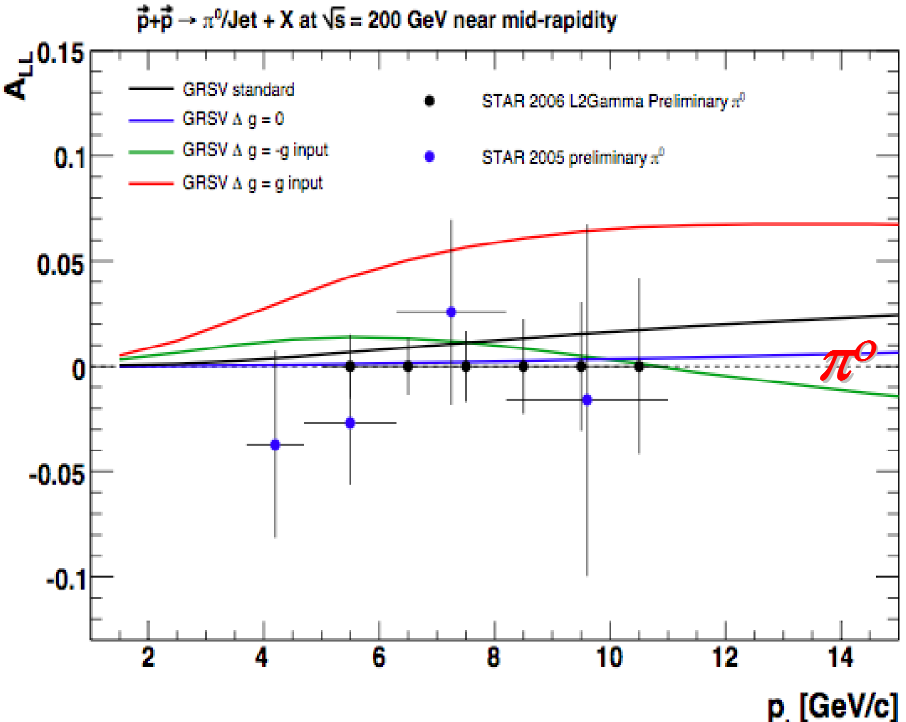
- ✓ Only exp. stat. uncertainties are included (the effect of syst. uncertainties is expected to be small in the final results)
- ✓ Theoretical uncertainties are not included

Summary- Bazilevsky (PHENIX) at Pacific SPIN07

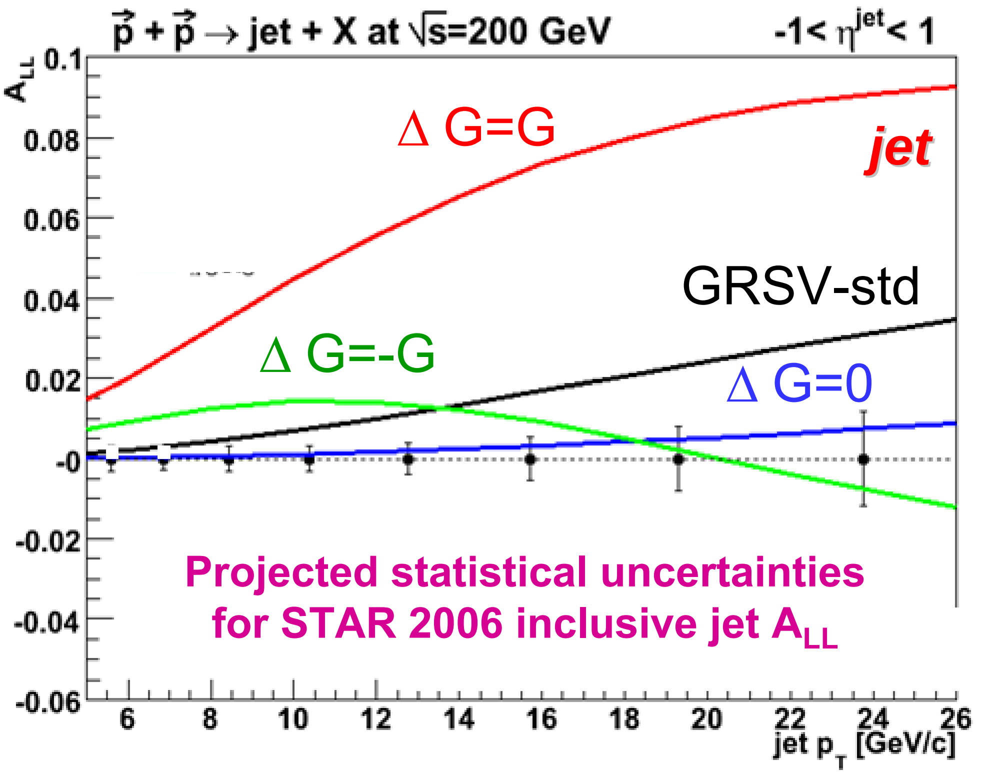
- RHIC is the world's first and the only facility which provides collisions of high energy polarized protons
  - ✓ Allows to directly use strongly interacting probes (parton collisions)
  - ✓ High $\sqrt{s} \Rightarrow$ NLO pQCD is applicable
- Inclusive $\pi 0$ accumulated data for A_{LL} has reached high statistical significance to constrain ΔG in the limited x range (~0.02–0.3)
  - ✓ ΔG is consistent with zero
  - ✓ Theoretical uncertainties might be significant
- Extending x coverage is crucial
  - ✓ Other channels from high luminosity and polarization
  - ✓ Different $\sqrt{s}$
- PHENIX upgrades strengthen its capability in nucleon spin structure study
  - ✓ Larger x-range and new channels (e.g. heavy flavor)
  - ✓ W measurements for flavor decomposition

Inclusive Jet (π^0) Data from 2006 -> Greater Discr'm Power for Δg

➢ *High-statistics (esp. at high p_T) inclusive jet and π^0 A_{LL} data from 2006 will select among Δg models, assuming a shape of $\Delta g(x,Q^2)$.*



W. Jacobs (STAR) – Pacific-SPIN07



- Significant increase in sampled luminosity
- Polarization typically ~60%
- acceptance in BEMC increased by a factor of 2
- also analysis w/ Endcap EMC
- π+ vs. π- analysis in Barrel

COMPASS

High p_T, $Q^2 < 1\,\mathrm{GeV}^2/c^2$: Result

Systematic Error

asymmetry extraction	0.014
Monte Carlo tuning	0.052
resolved photon PDF	0.013

Result (preliminary)

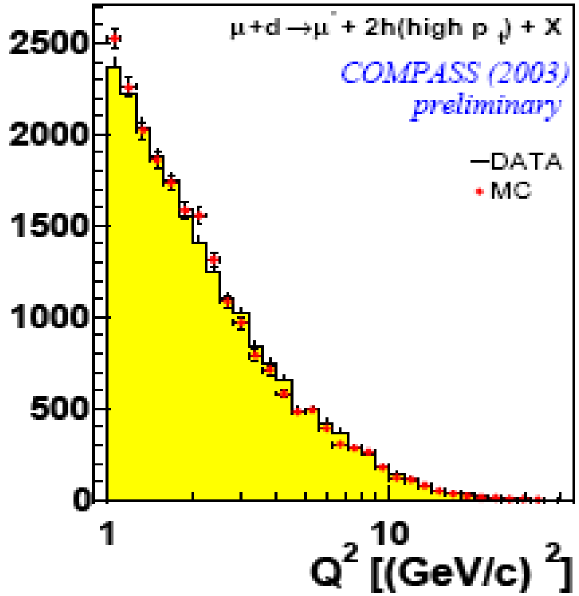
$$\frac{\Delta G}{G} = 0.016 \pm 0.058_{\mathrm{stat}} \pm 0.055_{\mathrm{syst}}$$

$$x_g \approx 0.085$$

$$\mu^2 \approx 3\,\mathrm{GeV}^2/c^2$$

est. for 2002–2006: $\delta_{\mathrm{stat}} = 0.045$

High p_T, $Q^2 > 1\,\mathrm{GeV}^2/c^2$

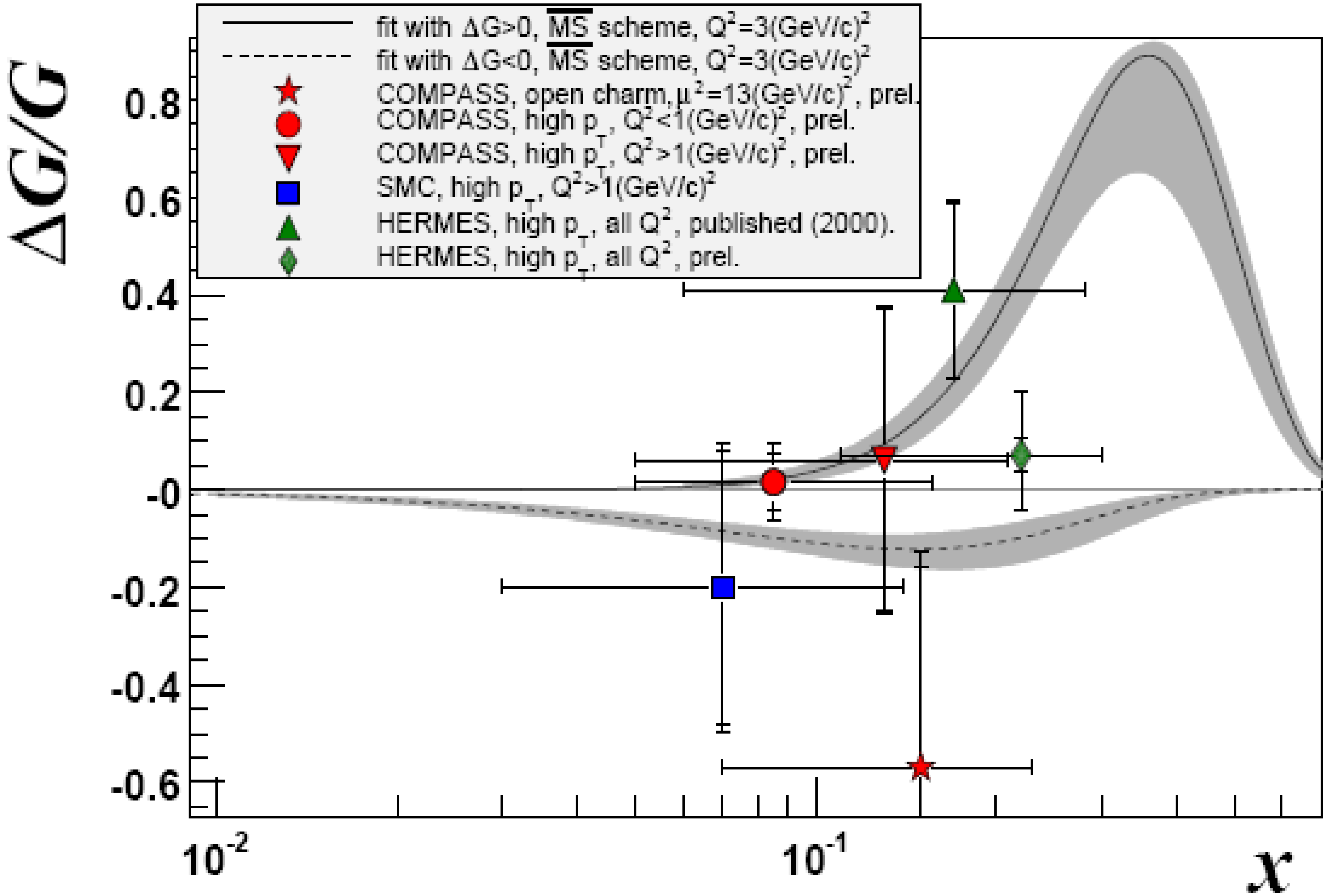


- resolved photon effects negligible
- MC using LEPTO+RADGEN
- $R_{PGF} = 0.34 \pm 0.07$
- new analysis with considerable improvement under way, using better cuts and full statistics (est. for 2002–2006: $\delta_{\text{stat}} = 0.14$)

Result (preliminary, 2002–2003 only)

$$\frac{\Delta G}{G} = 0.06 \pm 0.31_{\text{stat}} \pm 0.06_{\text{syst}} \qquad (x_g \approx 0.13, \mu^2 \approx 3\,\mathrm{GeV}^2/c^2)$$

Gluon polarisation



- bands correspond to statistical errors
- uncertainty due to parameterization not included

Kabuβ - Pacific-SPIN07

Hermes

Conclusions – N. Bianchi Pacific-SPIN07

$\Delta G/G$ has been extracted by HERMES using two different methods

Method I

$$\Delta G/G(x,\mu^2) = 0.078 \pm 0.034(\mathrm{stat}) \pm 0.011\,(\text{sys-exp})^{+0.125}_{-0.082}\,(\text{sys-model})$$

Method II

$$\Delta G/G(x,\mu^2) = 0.071 \pm 0.034(\mathrm{stat}) \pm 0.010\,(\text{sys-exp})^{-0.127}_{-0.105}\,(\text{sys-model})$$

Syst. model uncertainties still dominating (PDFs, PYTHIA model)

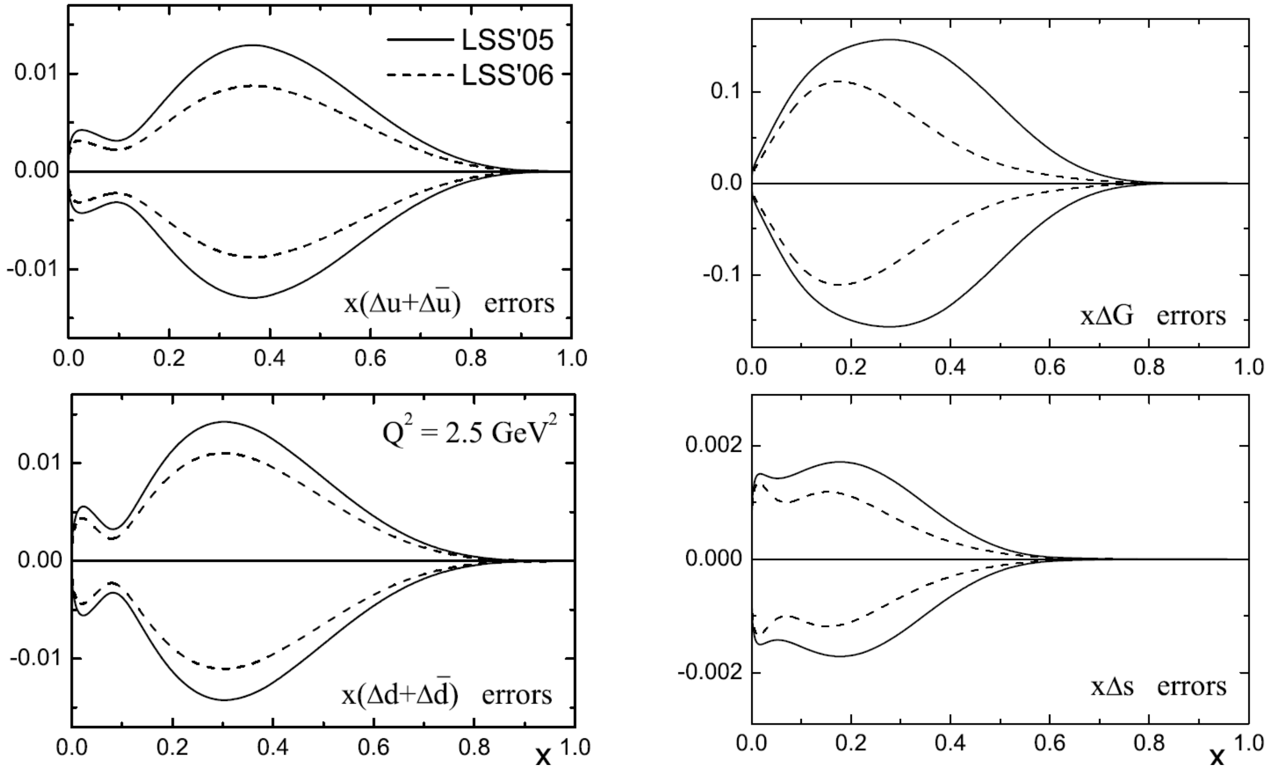
ΔG/G is likely small
and unlikely to solve the puzzle of the nucleon missing spin

JLab

Impact of CLAS Precision Data on Parton Distribution Functions

CLAS precision data more than doubled the data points in the DIS region from 30 years of high energy polarized structure function measurements.

The much improved control of higher twist (HT) effects achieved with these data allows to use them in global fits of the world data to extract PDFs.



At moderate x_B=0.4, the relative uncertainty of $x\Delta G$ is reduced by a factor 3 and of Δs-$\Delta\bar{s}$ by a factor 2.

Conclude
$|\Delta G| < 0.3$
at $Q^2 = 1$ GeV^2

The dashed lines include the CLAS data in the analysis (LSS'06).

E. Leader, A. Sidorov, D. Stamenov, Phys.Rev.D75:074027,2007.

First moment of g_1

$$\Gamma_1^{\mathrm{N}} \ (Q^2 = 3(\mathrm{GeV/c})^2) = \int_0^1 g_1^{\mathrm{N}} \mathrm{d}x$$

$$= 0.0502 \pm 0.0028(\mathrm{stat}) \pm 0.0020(\mathrm{evol.}) \pm 0.0051(\mathrm{syst.})$$

- data for $0.004 < x < 0.7$, QCD fit used for extrapolation
- contribution of unmeasured region about 3 %
- using: $\Gamma_1^{\mathrm{N}} = \frac{1}{9}(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha + s^2))(a_0(Q^2) + \frac{1}{4}a_8)$

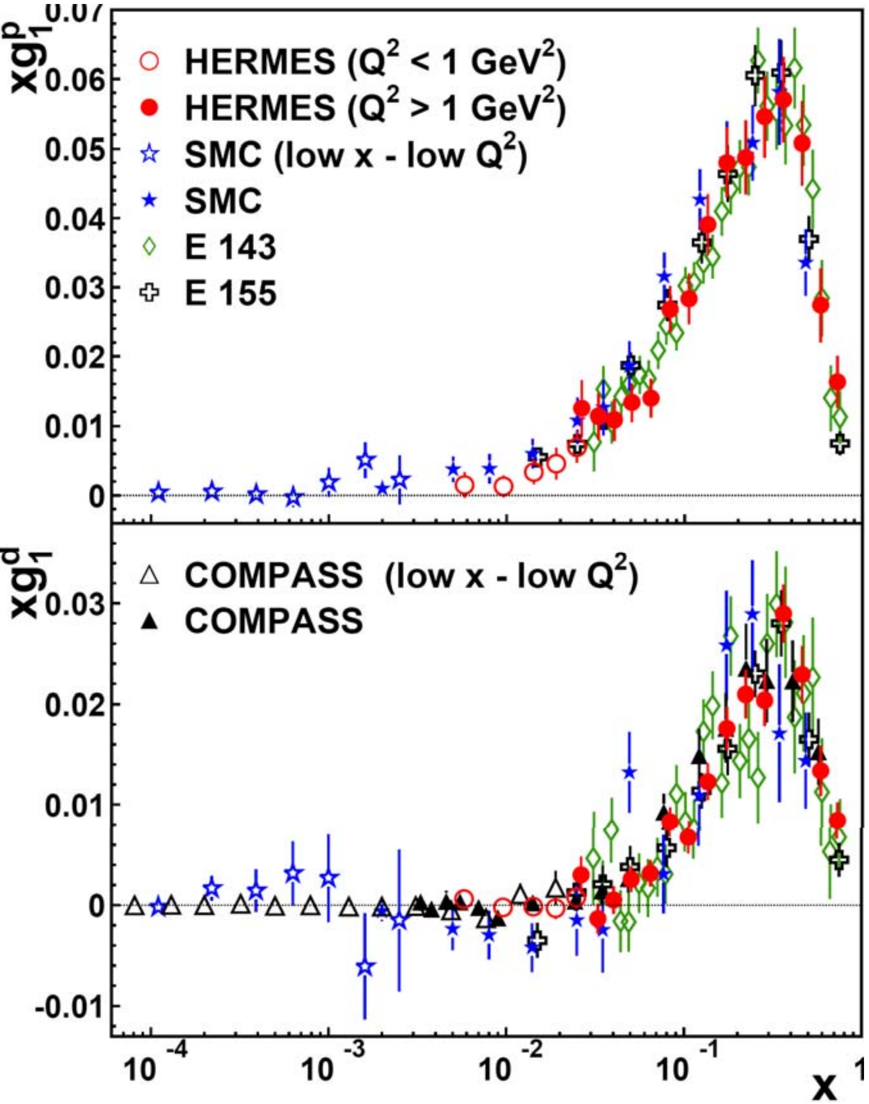
$$a_0(Q^2 = 3(\mathrm{GeV/c})^2) = 0.35 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

- extrapolating towards $Q^2 \to \infty$: $\boxed{\hat{a}_0 = 0.33 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst}) = \quad \Sigma}$

i.e. Now more like 1/3rd of proton spin carried by quarks

Kaβus – Pacific-SPIN07

From HERMES fit: similar results



$$a_0 = 0.330 \pm \underset{\text{(theory)}}{0.011} \pm \underset{\text{(exp)}}{0.025} \pm \underset{\text{(evol)}}{0.028}$$

Bradamante Erice 0907

$$a_0 = 0.33 \pm 0.03^{\text{(stat)}} \pm 0.05^{\text{(sys+evol)}}$$

$$\Delta\Sigma = a_0 \text{ in } \overline{\text{MS}}$$

Where is the Spin of the proton?

- **Modern data yields:**
  $\Sigma = 0.33 \pm 0.03 \pm 0.05$

  (c.f. $0.14 \pm 0.03 \pm 0.10$ originally)

- **In addition, there is little or no polarized glue**
  - **COMPASS: $g^D_1 = 0$ to $x = 10^{-4}$**
  - **A_{LL} (π^0 and jets) at PHENIX & STAR $\rightarrow \Delta G = 0$**
  - **Hermes, COMPASS and JLab: $\Delta G / G$ small**

- **Hence: axial anomaly plays little or no role in explaining the spin crisis**

- **Return to alternate explanation lost in 1988 in rush to explore the anomaly**

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One-Gluon-Exchange Correction

PHYSICAL REVIEW D VOLUME 38, NUMBER 5 1 SEPTEMBER 1988

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Since manuscripts submitted to this section are given priority treatment both in the editorial office and in production, authors should explain in their submittal letter why the work justifies this special handling. A Rapid Communication should be no longer than 3½ printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but, because of the accelerated schedule, publication is not delayed for receipt of corrections unless requested by the author or noted by the editor.

Spin structure functions and gluon exchange

F. Myhrer
Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208

A. W. Thomas
*Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, South Australia 5000, Australia and Department of Theoretical Physics, Oxford University, Oxford OX1 3NP, Oxfordshire, England**
(Received 13 June 1988)

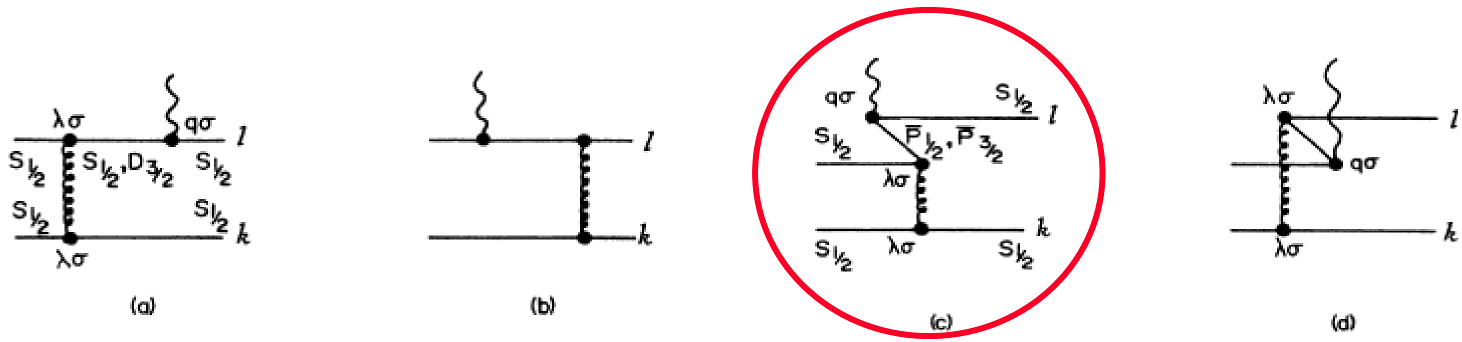
Two-quark correlations due to gluon exchange give corrections to both the proton and neutron spin-dependent structure functions in the Bjorken sum rule. They are found to be as large as the pionic corrections in the cloudy bag model of the nucleon. While still not enough to explain the result published recently by the European Muon Collaboration, it is compatible with the reanalysis of the data by Close and Roberts.

SU(6) violations due to one-gluon exchange

H. Høgaasen
Fysisk Institutt, University of Oslo, Blindern, 0316 Oslo 3, Norway

F. Myhrer
Department of Physics, University of South Carolina, Columbia, South Carolina 29208
(Received 26 October 1987)

The one-gluon-exchange corrections to the baryon magnetic moments and the weak semileptonic decays are shown to have the correct two-body operator in order to explain recent data. An explicit model calculation using a mode sum for the quark propagator is then performed. In this model calculation the two lowest states dominate the corrections. This value of SU(6) breaking explains the measured ratio $\Sigma^- \rightarrow ne\bar{\nu}/\Lambda \rightarrow pe\bar{\nu}$ as well as why $\mu_{\Xi^-} < \mu_\Lambda$ and it restores $\mu_p/\mu_n \simeq -\frac{3}{2}$ in chiral bag models.



Intermediate quark state contributing M	Intermediate quark energy	$10^4\Delta\mu$	$10^4\Delta g_A$	Intermediate quark energy M	$10^4\Delta\mu$	$10^4\Delta g_A$
$S'_{1/2}$	$5.40/R$	22	32	$8.58/R$	1.0	2.2
$D_{3/2}$	$5.12/R$	8	12	$8.41/R$	0.4	0.8
$\bar{P}_{1/2}$	$3.81/R$	730	-275	$7.00/R$	-6.7	7.0
$\bar{P}_{3/2}$	$3.20/R$	1349	-332	$6.76/R$	-6.1	6.0
Sum		2109	-563		-11.4	16.0

OGE Correction for Hyperon β-decay

- All correction terms proportional to $G = \alpha_s$ times bag matrix elements
- Very nicely accounts for deviations from SU(3) symmetry

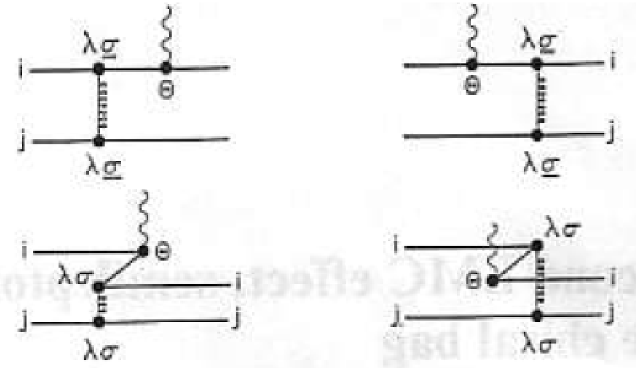


Table 1. The ratio g_A/g_V in the $SU(3)$ limit from a model calculations compared to experiments. The experimental numbers are from the Particle Data Group [32]

	Theory: MIT bag + CMI	$SU(3)$ amplitudes	Experiments
$n \to p$	$\frac{5}{3}B' + G = 1.25$	$F + D$	1.259
$\Sigma^- \to n$	$-\frac{1}{3}B' - 2G = -0.34$	$F - D$	-0.36 ± 0.05
$\Lambda \to p$	$B' = 0.72$	$F + D/3$	0.696 ± 0.025
$\Xi^- \to \Lambda$	$\frac{1}{3}B' - G = 0.19$	$F - D/3$	0.25 ± 0.05

F = 0.45 (fixed)
D = 0.81
D = 0.74
D = 0.60

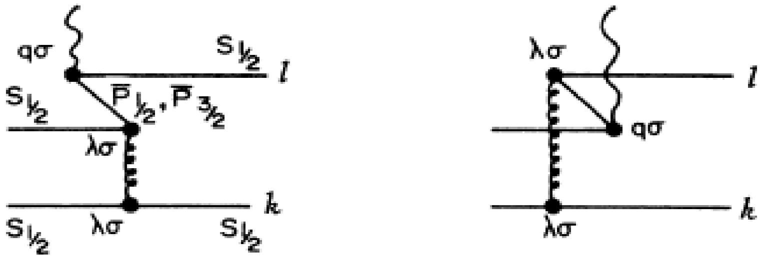
Hoggaasen & Myhrer, Z. Phys. C48 (1990) 295

One-Gluon-Exchange Correction

- Has the effect of further reducing the fraction of spin carried by the quarks in the bag model (naively 0.65) because of lower Dirac component of wave function (/// result in any relativistic model - e.g. recent work of Cloet et al., hep-ph/0708.3246, 0.67 in confining NJL model)

- $\Sigma \rightarrow \Sigma - 3G$; with $G \sim 0.05$

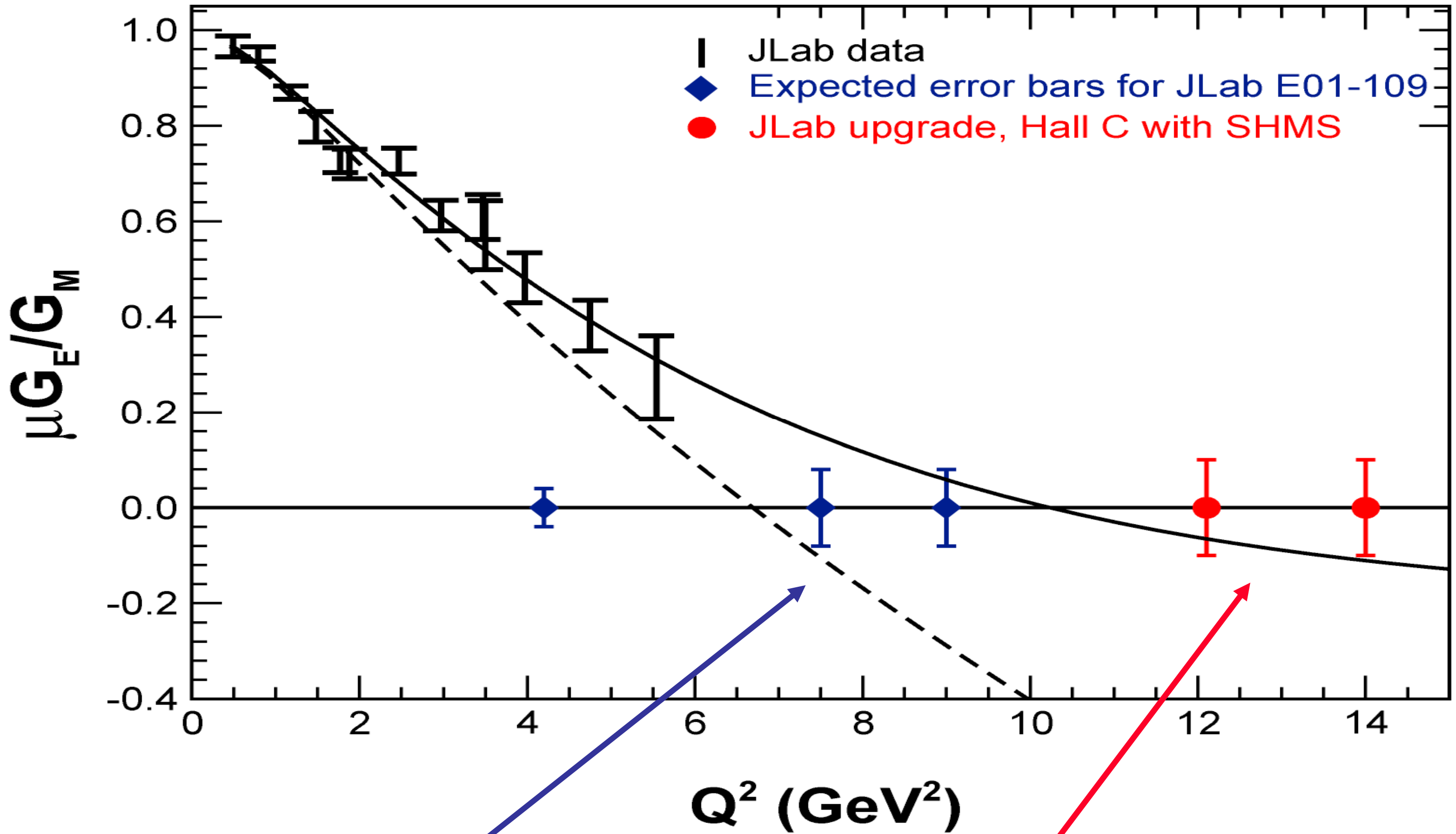
  $\Sigma \rightarrow 0.65 - 0.15 = 0.5$



(c) (d)

- Effect is to transfer quark spin to quark (relativity) and anti-quark (OGE) orbital angular momentum

Measurements of G_E^p – Relativistic Motion Critical



- Perdrisat *et al*. E01-109 — will increase range of Q^2 by 50% in FY08 (range of Q^2 for neutron will double over next 3-4 years)
- **With 12 GeV and SHMS in Hall C : similarly for G_M^n (and G_E^n)**

The Pion Cloud of the Nucleon

Volume 215, number 1 PHYSICS LETTERS B 8 December 1988

SPIN DEPENDENT STRUCTURE FUNCTIONS IN THE CLOUDY BAG MODEL

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Received 17 May 1988

We derive expressions for the integrals of the spin dependent structure functions $g_1(x)$ for the proton and the neutron in the context of the cloudy bag model. We find that the neutron contributes 5–10% to the Bjorken sum rule, while there is a corresponding decrease for the proton's contribution. It is difficult to reconcile these results with those reported in a recent experiment.

The Structure of the Nucleon

Anthony W. Thomas and Wolfram Weise

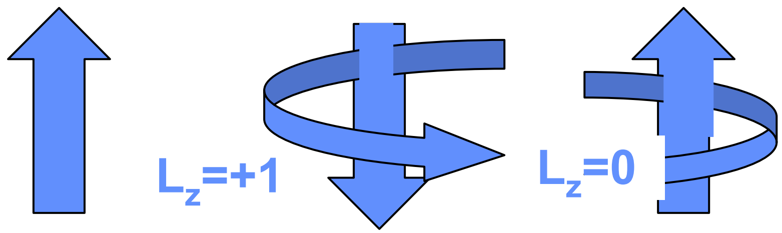
Thus for many purposes it is possible to think of the physical proton as consisting, some of the time (probability Z) of three valence quarks and some of the time as a pion plus a nucleon core (probability $P_{N\pi}$) and some of the time a pion and three valence quarks with the quantum numbers of a Δ (i.e., a "bare" Δ) – with probability $P_{\Delta\pi}$. There is considerable phenomenological evidence pointing to values for these probabilities of order $P_{N\pi} \sim 20\,\%$ and $P_{\Delta\pi} \sim 10\,\%$ [ST 97, Th 84].

8.5 Chiral Quark Models 237

Effect of the Pion Cloud

- Probability to find a bare N is Z ~ 70%

- Biggest Fock Component is N $\pi \sim$ 20-25% and 2/3 of time N spin points down



$Z \qquad \frac{2}{3} P_{N\pi} \qquad \frac{1}{3} P_{N\pi}$

- Next biggest is $\Delta\,\pi \sim$ 5-10%

- To this order (i.e. including terms which yield LNA and NLNA contributions):

- Spin gets renormalized by a factor :

$$Z - 1/3\, P_{N\pi} + 15/9\, P_{\Delta\pi} \sim 0.75 - 0.8$$

$$\Rightarrow \Sigma = 0.65 \rightarrow 0.49 - 0.52$$

Support for Pion Cloud Picture

- **Most spectacular example is the prediction* of $\bar{d} > \bar{u}$, because of the pion cloud ($p \to n\, \pi^+$)**

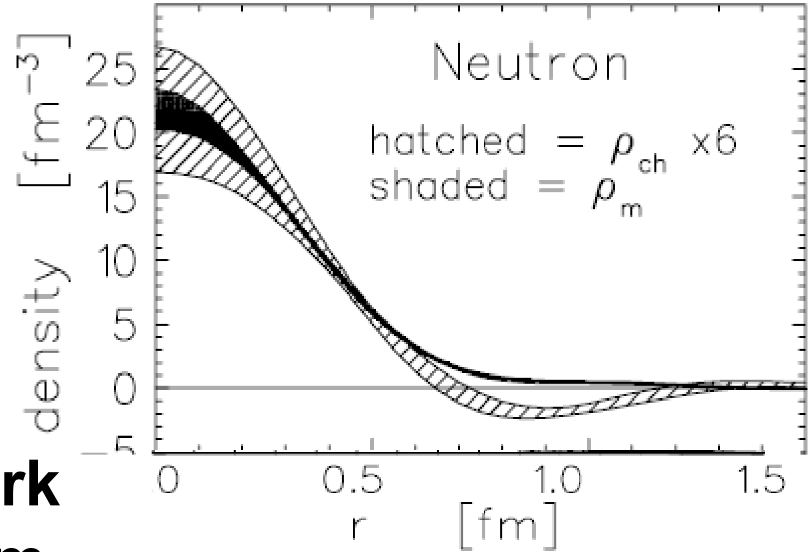
$$\int_0^1 dx\, [\, \bar{d} - \bar{u}\,] = 2\, P_{N\pi}/3 - P_{\Delta\pi}/3$$
$$\in 0.11 - 0.15$$

(in excellent agreement with latest data)

J.J. Kelly

* Thomas, Phys. Lett. B126 (1983) 97

- **Charge distribution of the neutron**



- **Natural understanding of quark mass dependence of data from lattice QCD (later)**

Can one add OGE and Pion Corrections?

- Prime phenomenological need for OGE interaction is the hyperfine splitting of N and Δ masses, Λ and Σ masses, etc. – i.e. hadron spectroscopy

- In early days of chiral models believed some of this hyperfine splitting came from pion self-energy differences

- Maybe double counting to include correction to Σ from both pions and OGE??

- Modern understanding NO: from analysis of data in quenched (QQCD) and full QCD, from Lattice QCD - implies 50 MeV (or less) of $m_\Delta - m_N$ in this way

Young et al., Phys. Rev. D66 (2002) 094507

Final Result for Quark Spin

$$\Sigma = (Z - P_{N\,\pi}/3 + 5\, P_{\Delta\,\pi}/3) \times (0.65 - 3\, G)$$

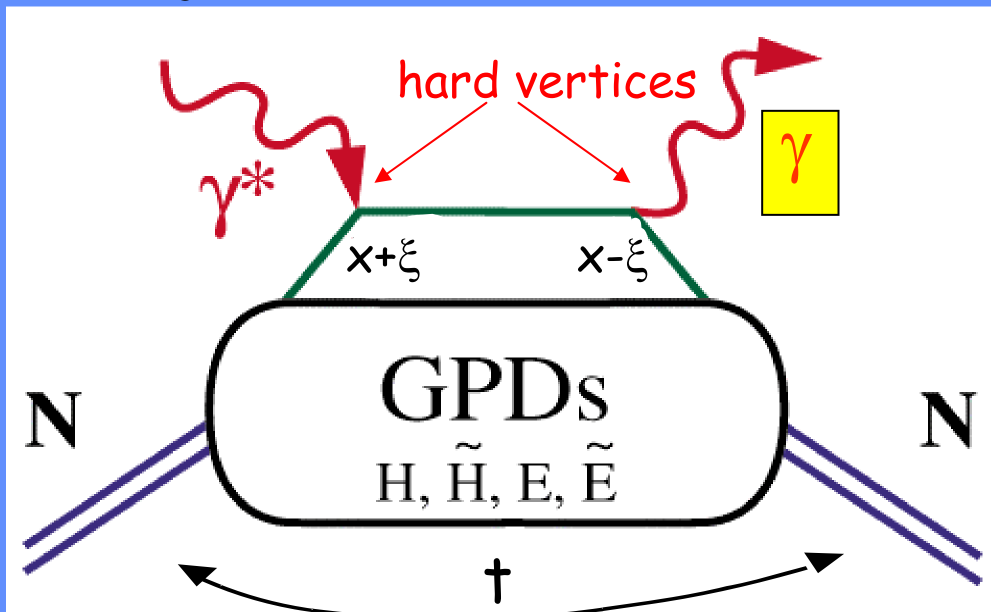
$$= (0.7,0.8) \times (0.65 - 0.15) = (0.35, 0.40)$$

c.f. Experiment: $0.33 \pm 0.03 \pm 0.05$

- ALL effects, relativity and OGE and the pion cloud have the effect of swapping quark spin for valence orbital angular momentum and anti-quark orbital angular momentum (>60% of the spin of the proton)

GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

At large Q^2 : QCD factorization theorem → hard exclusive process can be described by 4 transitions (Generalized Parton Distributions) :

Vector : $H(x, \xi, t)$

Tensor : $E(x, \xi, t)$

Axial-Vector : $\tilde{H}(x, \xi, t)$

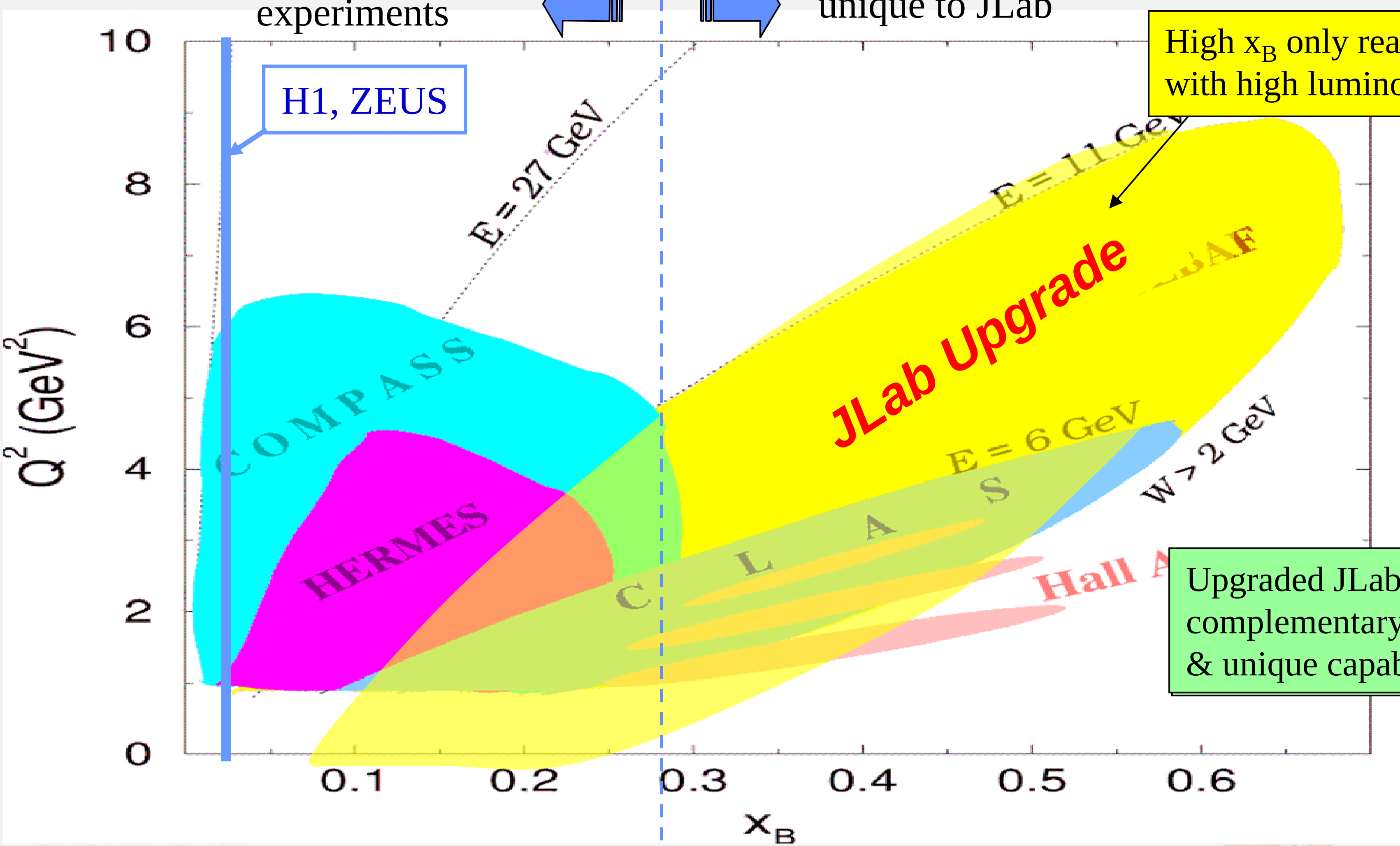
Pseudoscalar : $\tilde{E}(x, \xi, t)$

Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade

overlap with other experiments

unique to JLab

High x_B only reachable with high luminosity



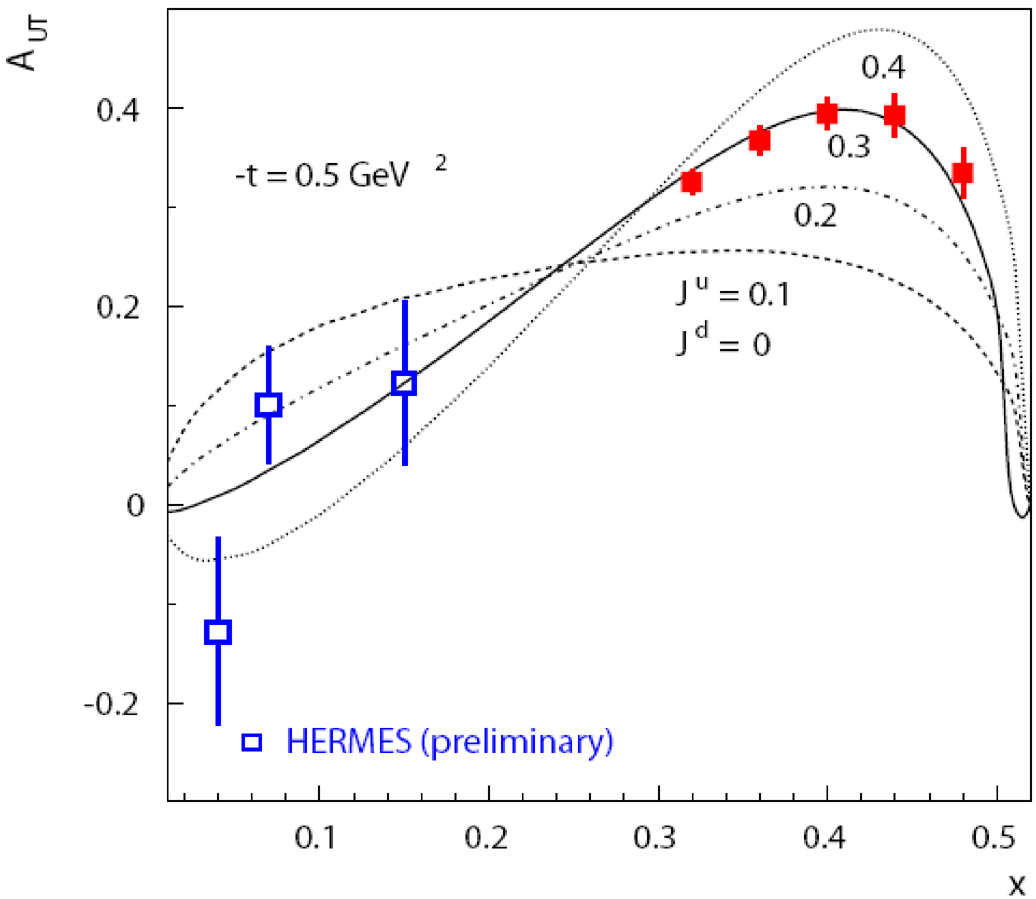
Upgraded JLab has complementary & unique capabilities

At 12 GeV: e.g. Exclusive ρ^0 with transverse target expect to determine quark orbital angular momentum

$$A_{UT} = -\frac{2\Delta\,(\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

$\boxed{\rho^0}$

$A \sim (2H^u + H^d)$
$B \sim (2E^u + E^d)$



$Q^2 = 5\,\mathrm{GeV}^2$

Asymmetry depends linearly on the GPD E, which enters Ji's sum rule.

K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001

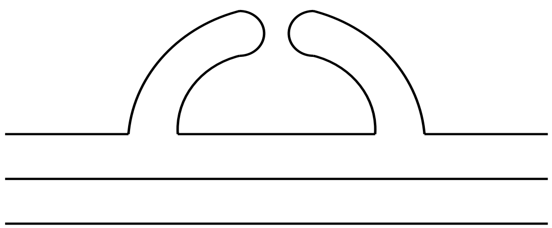
Confidence in Pion Self-Energies

- Recall: this is required for combining OGE and pion exchange corrections to spin problem
- Study the quark mass dependence of N and Δ masses in both QQCD and full QCD – in same lattice approach (same systematic errors), both CP-PACS and MILC data

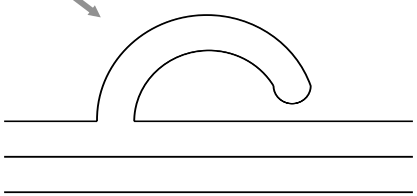
Analysis of N and Δ Masses in QQCD

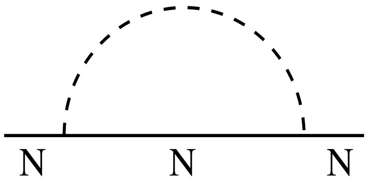
η' is an additional Goldstone Boson , so that:

$$m_N = m_0 + c_1 m_\pi + c_2 m_\pi^2 + c_3 m_\pi^3 + c_4 m_\pi^4 + m_\pi^4 \ln m_\pi + \ldots..$$



Contribution from η' and π





LNA term now ~ $m_q^{1/2}$

origin is η' double pole

Extrapolation of N Mass in QQCD

Coefficients of non-analytic terms again model independent

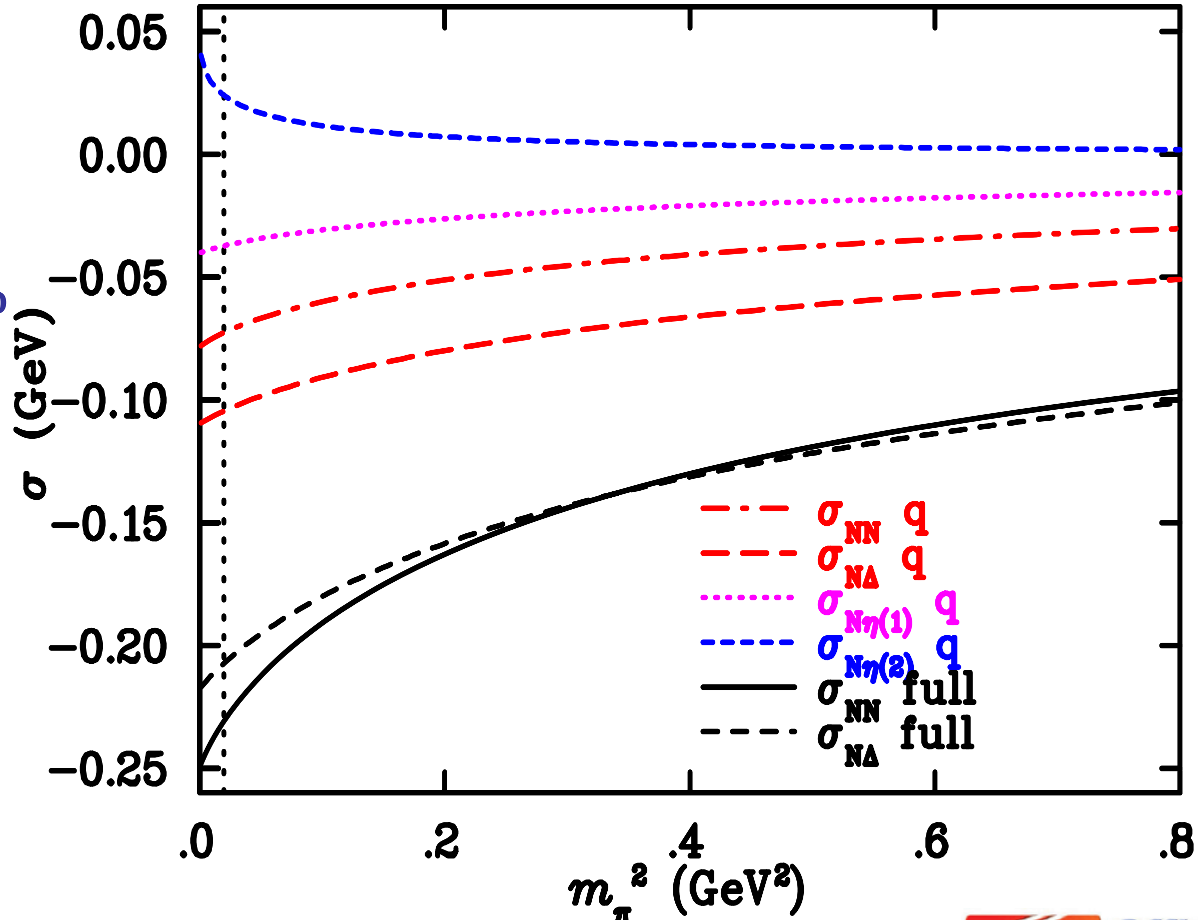
(Given by: Labrenz & Sharpe, Phys. Rev., D64 (1996) 4595)

Let:

$m_N = \alpha' + \beta' m_\pi^2 + \sigma_{QQCD}$

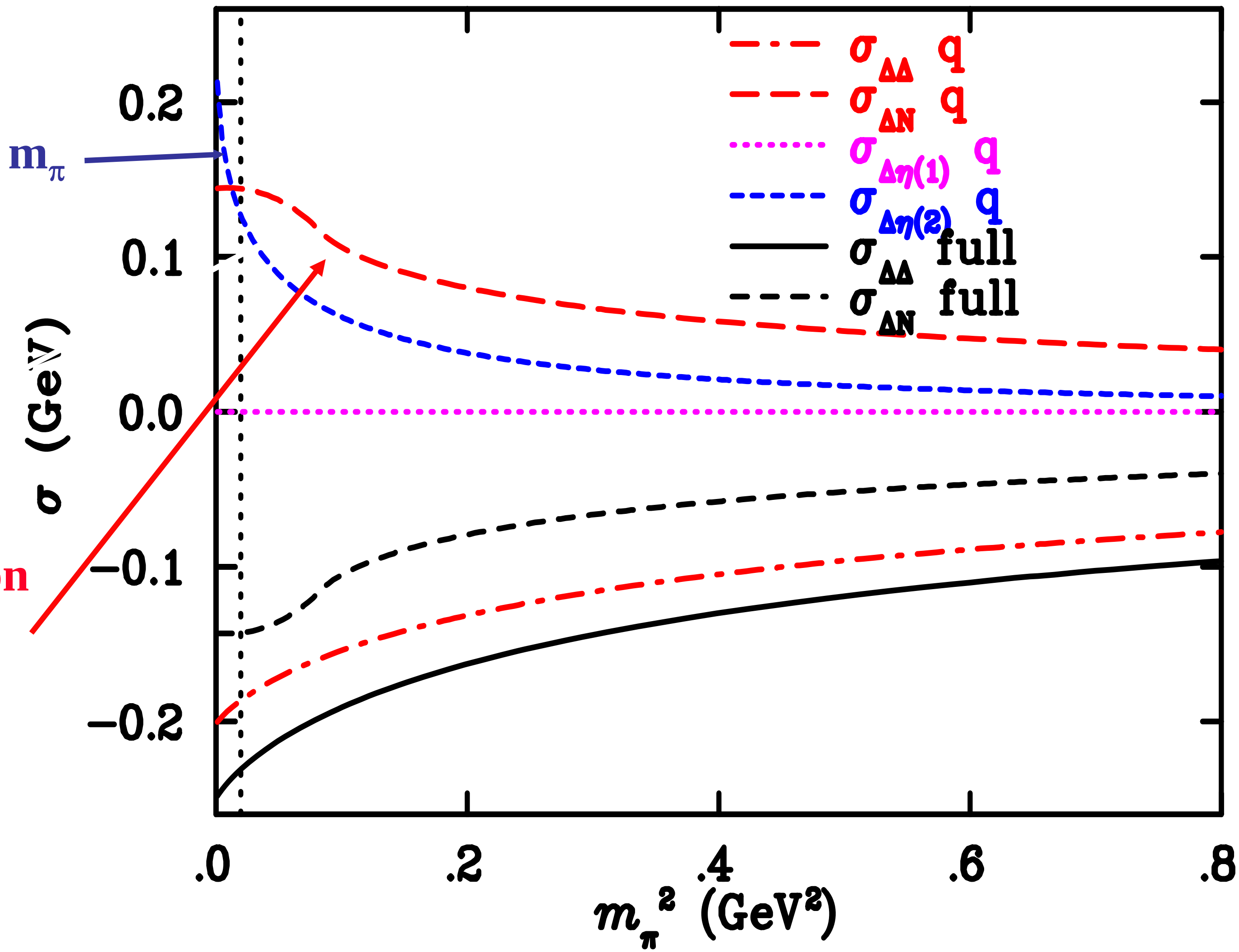
with same Λ as

full QCD



Analysis of Δ Mass in QQCD

LNA term linear in m_π



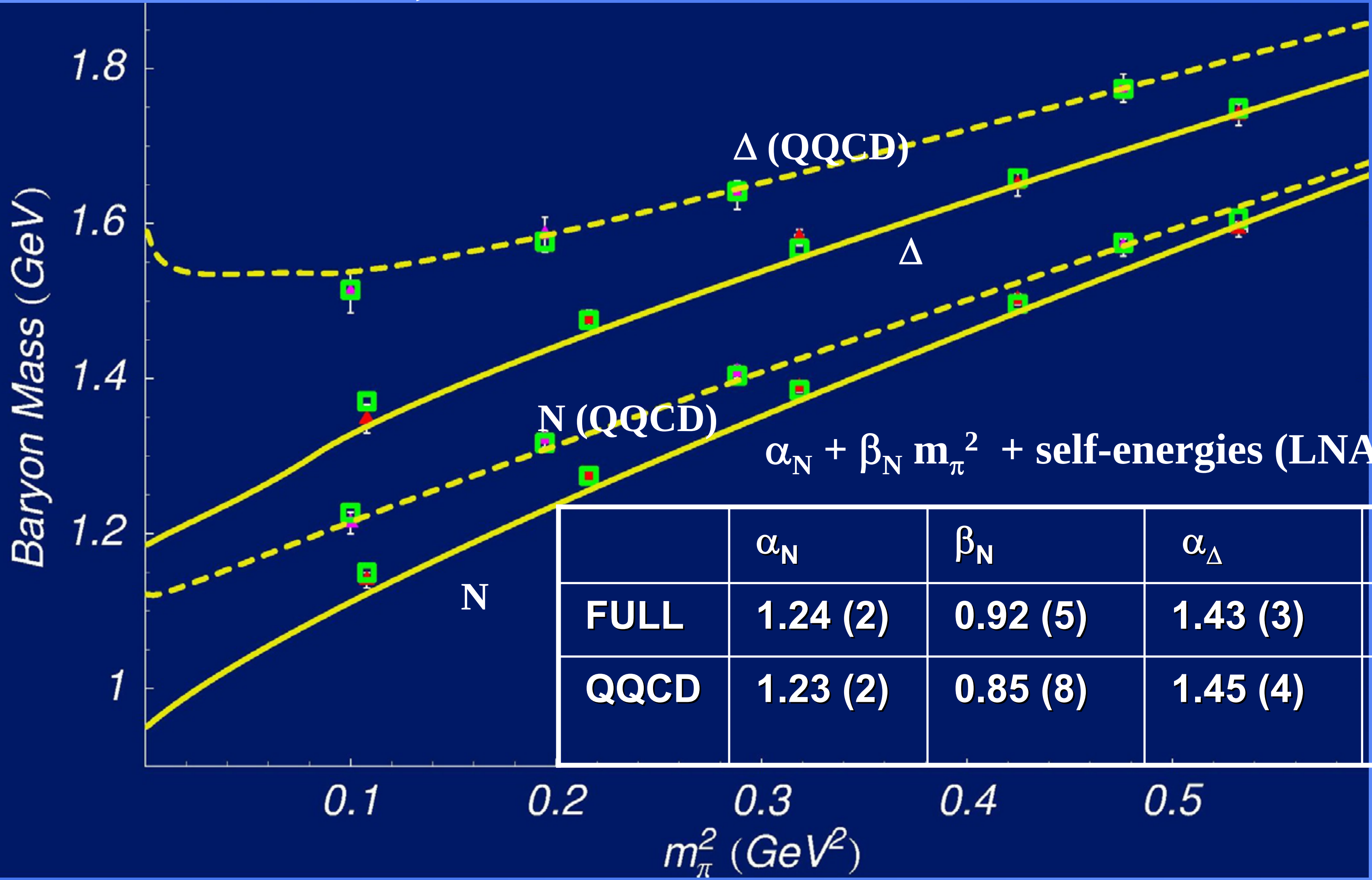
$\Delta \to N\,\pi$ contribution has opposite sign in QQCD (repulsive)

Overall σ_{QQCD} is repulsive !

•Lattice data (from MILC Collaboration) : red triangles

•Green boxes: fit evaluating σ's on same finite grid as lattice

•Lines are exact, continuum results

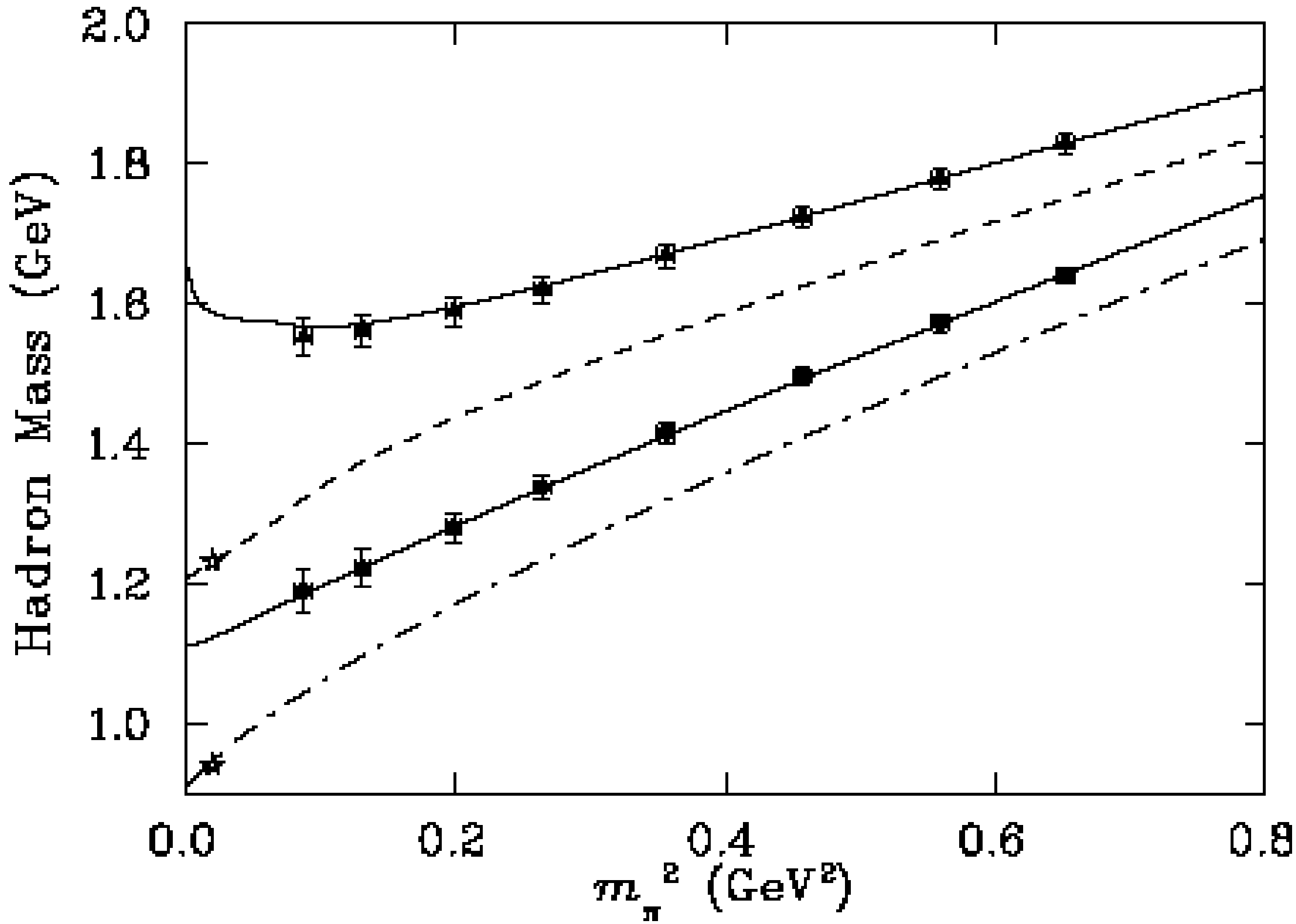


$\alpha_N + \beta_N m_\pi^2$ + self-energies (LNA+NLNA)

	α_N	β_N	α_Δ	β_Δ
FULL	1.24 (2)	0.92 (5)	1.43 (3)	0.75 (8)
QQCD	1.23 (2)	0.85 (8)	1.45 (4)	0.71 (11)

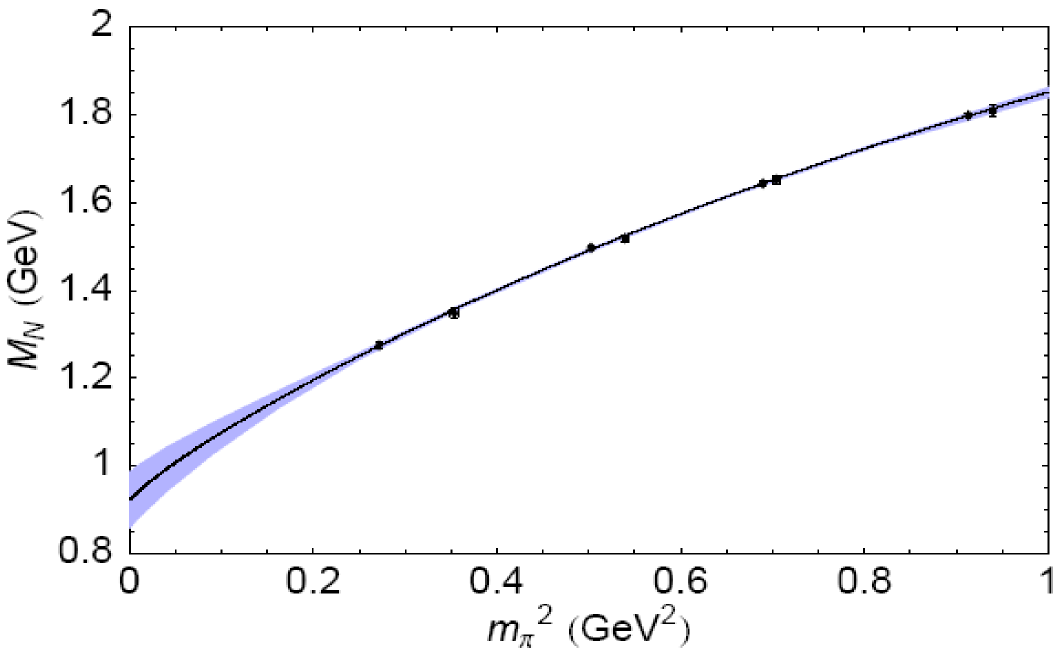
Young *et al.*, hep-lat/0111041; Phys. Rev. D66 (2002) 094507

Confirmation of Predicted Behavior of Δ



Zanotti et al., hep-lat/0407039
Lect. Notes Phys. 663 (2005) 199

χ'al Extrapolation Under Control when Coefficients Known – e.g. for the nucleon



FRR give same answer to <<1% systematic error!

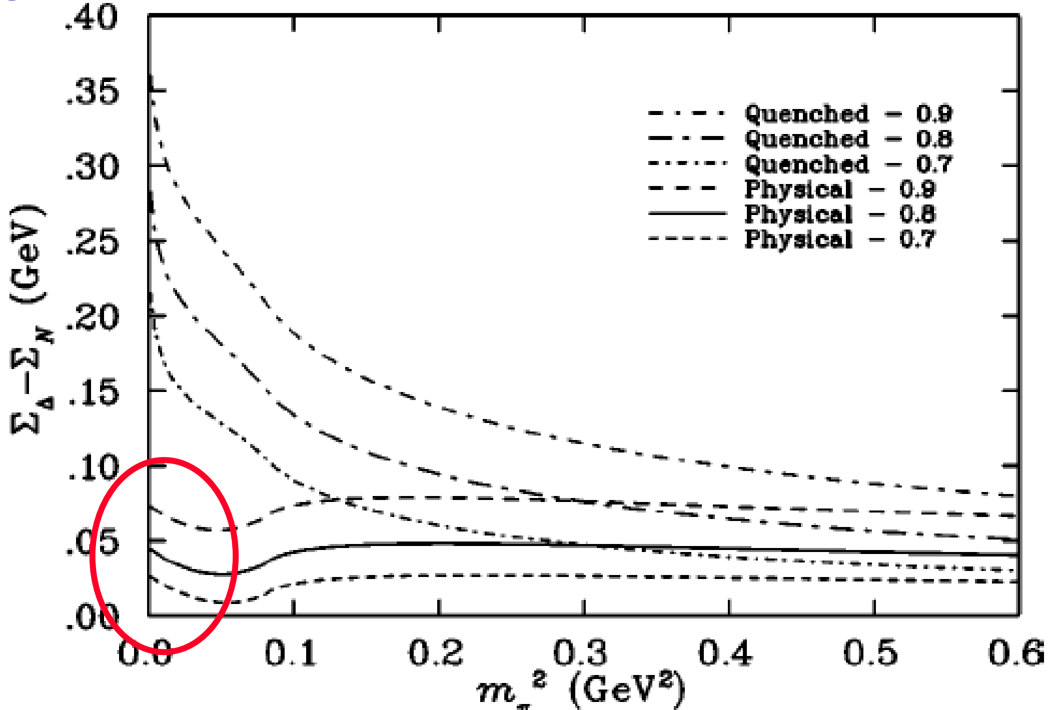
	Bare Coefficients				Renormalized Coefficients			
Regulator	a_0^Λ	a_2^Λ	a_4^Λ	Λ	c_0	c_2	c_4	m_N
Monopole	1.74	1.64	−0.49	0.5	0.923(65)	2.45(33)	20.5(15)	0.960(58)
Dipole	1.30	1.54	−0.49	0.8	0.922(65)	2.49(33)	18.9(15)	0.959(58)
Gaussian	1.17	1.48	−0.50	0.6	0.923(65)	2.48(33)	18.3(15)	0.960(58)
Sharp cutoff	1.06	1.47	−0.55	0.4	0.923(65)	2.61(33)	15.3(8)	0.961(58)
Dim. Reg. (BP)	0.79	4.15	+8.92	–	0.875(56)	3.14(25)	7.2(8)	0.923(51)

Leinweber et al., PRL 92 (2004) 242002

Nucleon - Δ Splitting

Lattice analysis
$\Rightarrow$ pions give 40 $\pm$ 20 MeV

PHYSICAL REVIEW D **66**, 094507 (2002)



- **Hence most of the N-Δ splitting comes from OGE – as in most quark models**

- **Thus the value of α_s used in the bag model calculation of the exchange current correction is more or less unchanged**

- **and… one can <u>add</u> the pion and OGE corrections to the spin sum-rule**

Operated by Jefferson Science Associates for the U.S. Department of Energy

Final Subtlety

- Connection between models and QCD must be at relatively low scale

- i.e. $\Sigma \in (0.35,0.40)$ calculated from pion cloud and OGE is really $\Sigma(\mu^2)$ with $\mu^2 < 1$ GeV^2

- To compare with Σ_{inv} we need a non-perturbative renormalization factor*: $\exp\left[\int_{\alpha(\mu)}^{0} da\, \gamma(a)/\beta(a)\right] \times \Sigma(\mu^2)$

- This is rigorously less than one and working to 3 loops# we get a factor $\in (0.6,0.8) \Rightarrow \Sigma_{inv} \in (0.21, 0.32)$

- Still in excellent agreement with latest data

* Bass, Crewther et al. PR D66 (2002)

Larin (&Vermasseren), PL B334 (1994)

Summary

- Two decades of experiments have given us important new insight into spin structure of the p

- U(1) axial anomaly appears to play little role in resolving the problem
  - not as severe as in original EMC paper

- Instead, important details of the non-perturbative structure of the nucleon DO resolve the "crisis"

  - OGE correction and pion cloud (+ relativity)

Summary

- Instead, important details of the non-perturbative structure of the nucleon DO resolve the "crisis"

  - OGE correction and pion cloud (+ relativity)

- Important consequence for quark model AND future experiments is that there is significant orbital angular momentum carried by valence quarks and anti-quarks in the proton

- Study of GPDs, especially at 12 GeV at JLab, will be crucial to verify this